Green Energy and Technology

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Green Energy and Efficiency

An Economic Perspective

Springer

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Foreword

Repsol Foundation and this Book

The Low Carbon Programme (LCP) is a joint initiative by the Basque Centre for Climate Change (BC3) and The University of the Basque Country (UPV-EHU) funded by the Repsol Foundation. The LCP was set up to promote research in energy economics and climate change and contribute to deliver a low carbon future.

Addressing climate change has become not only an environmental necessity, but also an economic opportunity and a mainstay of energy and economic policies. The reduction of carbon emissions, the expansion of renewable energy capability and the improvement of energy efficiency are three key elements for climate policy on a global level.

This book is devoted to the third of these key elements: energy efficiency. In doing so it reflects the Repsol Foundation's commitment to the matter and strives to help mainstream the concept of energy efficiency in a socially and economically inclusive manner.

The Repsol Foundation created the Energy Observatory in 2008 as part of its commitment to encouraging a new energy model and moving towards a new energy economy. One of the four priority lines of the observatory is the "Promotion of knowledge, research and innovation in areas related to energy and efficient energy use".

As part of the work of the Energy Observatory, the Repsol Foundation produces an annual technical report that tackling the challenge of assessing energy efficiency and the intensity of Greenhouse Gas (GHG) emissions in Spain and the European Union. Repsol's Energy Efficiency Index and the Repsol Energy Efficiency Social Indicator are the main novel measurement efforts used to better understand energy efficiency from a multi-conceptual approach. All this makes it possible to analyse trends in the relevant parameters with a view to assessing the impact of the policies designed to improve them, offering a view that complements that of conventional indicators.

All this is very much aligned with the aim of the book presented here: to provide state-of-the-art knowledge on the issue of energy efficiency economics. To that end we have gathered together contributions from internationally renowned experts in this interesting field under the editorial supervision of Alberto Ansuategi, Juan Delgado and Ibon Galarraga.

We believe that this book will contribute to the aims of the Repsol Foundation of moving towards a new way of understanding society and energy as two sides of the same coin.

César Gallo

Contents

Introduction

Energy efficiency technologies represent a key driver for the reduction of energy demand through a more efficient use of energy. The progressive switch to green sources of energy allows using the same amount of energy while reducing carbon emissions. The combination of measures to increase the efficient use of energy and to switch to cleaner sources of energy allows reducing energy demand and reducing the emissions per unit of energy produced. Energy efficiency and the development of alternative sources of clean energy are key elements for the attainment of global climate objectives.

The cost and effectiveness of efficiency measures and of the transition to a greener energy world is not however absent of controversy. This book presents up-to-date research on the economics of green energy and energy efficiency from a variety of perspectives, from a general overview of the economics of green energy and efficiency to the detailed analysis of specific policies and investment decisions.

The book starts by providing a general overview on the economics of green energy and efficiency, on the EU policies in this field and on valuation methods for energy and climate investment.

Energy efficiency and green energy contribute to expanding the production frontier of the economy relaxing the 'limits to growth' imposed by the traditional energy sources. In this sense, climate policies not only solve market failures, but also have important consequences on established macroeconomic paradigms. M.C. Gallastegui, M. Escapa and A. Ansuategi "Green Energy, Efficiency and Climate Change: An Economic Perspective" analyse the economic microfoundations of climate policies, identifying its key elements and the market failures they aim to solve, and the macroeconomic consequences of green energy and efficiency policies, in terms of changing the nature of energy from a limited input to a reproducible production factor, which has immediate expansive effects over the economy's production frontier.

Europe has become a scenario for the implementation and testing of new climate policy instruments. G. Sáenz de Miera and M.A. Muñoz Rodríguez "EU Policies and Regulation on CO_2, Renewables and Energy Efficiency: A Critical Assessment of Recent Experiences" review critically the EU climate policies over the last 20 years, which aim to bringing down CO_2 emissions, promoting renewable energies and enhancing energy efficiency.

Energy and climate policies require large investments which span over decades. The valuation of such investments is crucial for the design of policies and to evaluate the cost-effectiveness of such policies. L.M. Abadie "Economic Foundations of Energy Investments" examines fundamental issues in the valuation of energy investments under uncertainty, using the real options approach and market quotations. Valuation methods incorporate the existing uncertainty about the price of primary energy and the evolution of the carbon price.

The Part II presents state-of-the-art research in energy efficiency policies and their effectiveness.

Progress in terms of realising the energy efficiency potential has been limited. A. Markandya, X. Labandeira and A. Ramos "Policy Instruments to Foster Energy Efficiency" analyse why individual incentives to adopt energy efficiency measures are poor and how policies can address that problem and revert the incentives. The chapter reviews the range of policy tools available to incentivise the efficient use of energy focussing on their design and effectiveness.

Price signals are key drivers for promoting energy efficiency. The European Emissions Trading System (EU ETS) is the world largest market for carbon dioxide. J. Chevallier "Understanding the Link Between Aggregated Industrial Production and the Carbon Price" analyses the link between economic activity and the carbon price, recalling the main channel of transmission between the variation of macroeconomic activity and the carbon price set by the EU ETS.

Evidence to analyse the effectiveness of efficiency measures is limited, especially in the case of those measures based on solving information asymmetries that aim to change human behaviour. J. Lucas and I. Galarraga "Green Energy Labelling" analyse the effectiveness of one of those measures. In particular, they analyse the Willingness to Pay for Energy-Savings in refrigerators, dishwashers and washing machines in Spain. Their chapter provides new evidence on the effectiveness of labelling as an instrument to improve energy efficiency.

The magnitude of the rebound effect is essential when designing energy efficiency policies. A large rebound effect can offset the effects of an energy efficiency programme. P. Gálvez, P. Mariel and D. Hoyos "Estimating the Direct Rebound Effect in the Residential Energy Sector: An Application in Spain" estimate the direct rebound effect in residential heating and domestic hot water services in Spain. They find that the direct rebound effects are relatively high, so an increase in energy efficiency can be expected to produce only a slight decrease in consumption.

Efficiency measures normally require one-off investments whose benefits span over a period of time. Such initial investment and access to finance can constitute obstacles to the adoption of more efficient technologies. S. Bobbino, H. Galván and M. González-Eguino "Budget-Neutral Financing to Unlock Energy Savings Potential: An Analysis of the ESCO Model in Barcelona" present an increasingly popular business model known as the Energy Service Company (ESCO) model and identify the main obstacles to its widespread implementation both from the public and private perspectives. The ESCO model is essentially a 'budget neutral' method of financing the purchase, installation and maintenance of energy efficient technologies. This concept has been successfully implemented in the US, the UK and Germany. The chapter focusses on the analysis of the ESCO programme implemented in the city of Barcelona.

The rate of Innovation and of new technology adoption are crucial for the effectiveness of energy efficiency policies. Surprisingly, the demand for energy has not shown a decreasing trend over the last two decades. V. Constantini, F. Crespi, G. Orsatti and A. Palma "Policy Inducement Effects in Energy Efficiency Technologies: An Empirical Analysis of the Residential Sector" provide an empirical analysis of the drivers of innovation in energy efficiency technologies by looking at the residential sector and conclude that the innovation system at both national and sectoral levels, together with the environmental and the energy systems, have encouraged the propensity to innovate and significantly shaped the rate and direction of technical change in the residential sector.

The Part III presents research on the cost and effectiveness of the deployment of green energy. Although deemed as necessary in fighting climate change, the design of instruments to effectively promote green energy has not been absent of controversy. The proper combination of subsidies to deployment and subsidies to R&D is still to be determined.

Using the proper metric to assess the cost of renewable energy is essential to properly design a system of green energy promotion. I. Mauleón "The Cost of Renewable Power: A Survey of Recent Estimates" presents an overview of recent, up-to-date estimates of the cost of generating electric power from renewables. The results are based on actual data from projects already implemented or commissioned, and are organised as homogeneously and comparably as possible. Two main cost measures are considered: total capital costs, and its two main components, equipment, and remaining installation costs, and the Levelised Cost of Electricity.

The promotion of green energy should not be addressed as a policy in isolation of other climate policies. Policy instruments interact and if such interaction is not internalised in their design, their effectiveness can be reduced. P. Beato and J. Delgado "Interactions Between Climate Policies in the Power Sector" analyse theoretically and empirically the interactions between carbon markets and the instruments to promote the deployment of green energy in the power sector. They conclude that the optimal climate policy mix should be carefully designed to take into account the potential interactions between policy instruments in order not to undermine their effectiveness.

Whether green energy policies should focus on subsidising deployment or subsidising research, development and demonstration (RD&D) is an open question. G. Zachmann, A. Serwaah and M. Peruzzi "When and How to Support Renewables?—Letting the Data Speak" address this question empirically by analysing patenting behaviour and international competitiveness in 28 OECD countries over 20 years. They show that both deployment and RD&D coincide with increasing knowledge generation and improving competitiveness of renewable energy technologies. They find that both support schemes together have a higher effect than the two individually and that RD&D support is unsurprisingly more effective in driving patents. Thus, they conclude that both deployment and RD&D support are needed to create innovation in renewable energy technologies, but more empirical work is needed to determine the right policy mix.

The policy costs of support for renewable energy sources for the production of electricity (RES-E) have been object of controversy, especially in those countries where there is a large penetration of renewable energy in their electricity mix. P. del Río "Renewable Energy Promotion: Usual Claims and Empirical Evidence" reviews and discusses some usual claims about renewable energy promotion and checks whether such claims have theoretical and empirical foundations. The chapter sets a frame of undisputed evidence that opens fruitful avenues for further research on the topic.

The EU ETS has become the centrepiece of EU climate policies. The EU ETS not only 'punishes' CO_2 emitters but also creates incentives to innovate through non-emitting technologies. J. Martín Juez and C. González Molinos "The EU-ETS as an Environmental Instrument" evaluate the performance of the EU ETS after 8 years of operation. The chapter describes the evolution of the carbon price in the EU ETS and relates its dynamics with a number of different factors. The chapter also establishes lines of reform to improve its functioning.

The large-scale deployment of renewable energies has important implications for the electricity transmission network design and operation. It will require the transportation over long distances of large amounts of energy and will lead to less predictability and more stress in the use of the transmission network to cope with the intermittency and variability of such generation resources. L. Olmos, M. Rivier and I. Pérez Arriaga "Renewable Energy and Transmission Networks" identify and discusses the main impacts related to the existence of renewable generation on those aspects of the functioning of the system that are related to the transmission grid.

As a consequence of climate and energy efficiency policies, electricity generation mixes are deemed to change dramatically in the near future. Anticipating the evolution of the generation mix and its performance is essential to design future policies and guarantee that generation investment is sufficient to serve future demand. J.M. Chamorro, L.M. Abadie and R. de Neufville "Measuring Performance of Long-Term Power Generating Portfolios" propose a model for assessing the performance of generation mixes using the expected price of electricity and the price volatility that result from different generating portfolios that change over time. They make use of an optimization process subject to the behaviour of stochastic variables that minimises the total costs of electricity generation and delivery. The model helps decision makers in trying to assess electricity portfolios or supply strategies regarding generation infrastructures. The technique is illustrated through the analysis of the UK generation mix over the next 20 years.

Part I
Introduction

Green Energy, Efficiency and Climate Change: An Economic Perspective

M.C. Gallastegui, M. Escapa and A. Ansuategi

Abstract The three core objectives of any sensible energy policy nowadays are (1) security of supply, (2) competitiveness, and (3) sustainability. Renewable energy and energy efficiency investments are crucial if we are to make energy supplies more sustainable, competitive and secure. These goals support each other. More sustainable energy sources, such as renewables, help the energy sector to be more competitive, as well as diversifying and securing its energy supply. Yet implementing policies to promote green energy and efficiency is no easy task. This chapter seeks to discuss the difficulties facing the regulation needed in the energy sector and to analyze the key concepts and the main markets failures that characterize the energy markets. It also reviews the main policies undertaken at EU level in order to deal with the relations between the energy sector and the problem of climate change.

1 Introduction

Economists use an algebraic function which maps inputs into output as a tool to describe the determinants of production. Thus, macroeconomists use an aggregate "production function" which combines aggregate inputs typically including physical capital, labor and sometimes other inputs such as land[1] and energy. Production functions have more recently been extended to include natural and human capital. Technology and innovation represent the way the production possibilities of a

[1] Land was used to include all natural resource inputs to production and played a central role in the classical economic model. However, as its value share of Gross Domestic Product (GDP) fell steadily in the twentieth century [26], it gradually diminished in importance in economic theory and today is usually subsumed as a subcategory of natural capital.

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country change over time through the development of new inventions and techniques for production and they are embedded into the functional form of the production relationship.

This chapter focuses on the economics of energy and climate policy and the complexities confronting the regulation needed in the energy sector. The complexities are due to many factors. The basic one is that energy and electricity exert their influence over all economic sectors and citizens. Even though most of our analysis will be conducted from a microeconomic perspective, we consider that some remarks regarding the "macroeconomic" principles that govern energy and climate policy are also needed. Thus, we start by clarifying two key concepts in the economics of production that are often confused in this debate: reproducibility and the distinction between primary and intermediate inputs. With regard to reproducibility, it must be noted that some inputs to production are nonreproducible, while others can be manufactured within the economic production system. Capital and labor are reproducible factors of production, while energy is a nonreproducible factor of production. Although most economists continue to dismiss the ideas spelled out explicitly in the "Limits to Growth" report of the Club of Rome Meadows et al. [21] and even ecologists have largely shifted their attention away from exhaustibility of resources to focus on various threats to the biosphere, the question over the need to shift the energy paradigm from a nonrenewable (oil) era to a renewable (solar) era is still present in the energy policy debate. In fact, one of the justifications of the concern of many developed countries about energy security is related to the fear that the growing demand for imports of oil and gas by developing countries, especially China and India, will lead to greater worldwide dependence on and competition for a scarce resource [7].

With regard to the primary/intermediate nature of factors of production, primary factors are inputs that exist at the beginning of the period under consideration and are not directly used up in production, while intermediate inputs are those created during the production period under consideration and are used up entirely in production. Economists usually think of capital, labor, and land as the primary factors of production, while resources such as fuels are intermediate inputs. This explains the mainstream growth theory focus on the primary inputs, and in particular, capital and labor, and a lesser and somewhat indirect role of energy in the theory of production and growth. More recently some authors claim that "energy is actually a much more important factor of production than its small cost share may indicate" and that "a future scenario of shrinking reserves of fossil fuels and an increasingly stringent climate policy, with associated rising energy prices, has very negative implications for economic growth worldwide" [3].

Another distinctive feature of energy as compared to capital and labor is the environmental impact associated to its use. Global mean temperature has increased over the past 100 years. There is new and stronger evidence that most of the observed warming over the past 50 years is attributable to greenhouse gas (GHG) emissions from human activities, in particular to emissions of CO_2 (the most important GHG) from burning fossil fuels and land-use changes, and other GHGs from industry, transport, waste management, and agriculture. Industrialized countries rely on a carbon-intensive energy system. Substantial amounts of fossil fuels (coal, oil and natural gas) are burned, both in power and heat production and in all the sectors using energy.

According to the IPCC 5th report: “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.” Furthermore, “Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system” [15].

It is also well known that achieving the 2 °C target in the long term (after 2100) would require atmospheric GHG concentration levels well below 550 ppm CO_2 equivalent (broadly consistent with 450 ppm of CO_2 alone). Furthermore stabilization at 500 ppm requires that emissions be −7GtC/yr below Business as Usual in 2050 [24]. According to IPCC [16], to keep temperature increase below 2 °C emissions must be reduced in comparison to 2010 by 40–70 % by 2050 and by almost zero by 2100. This entails radical technological and institutional change, and an important transformation in lifestyles.

This ambitious objective is not easy to achieve. In fact how to encourage the use of energy sources, alternative to fossil fuels, is a difficult task facing numerous policy challenges. There is still not consensus about how this objective should be pursued and unsolved questions still remain, even though the real problems are pressing and a deal of work has to be undertaken in the theoretical and empirical analysis that tries to deal with these challenges [1].

In principle the objective can be achieved by pursuing energy efficiency, the decarbonization of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy and renewable energy) and using biological storage in forests and agricultural soils [8]. All these alternatives have been tried, in one or more countries, but the concrete structure of policy measures varies a great deal. The general movement towards the use of renewable sources of energy seemed to be a “focal point” some years ago. Now the question about whether renewable energy should be the central component of a low-carbon future is not as clear as the deep economic recession has put the high economic costs of this solution into perspective.

From the preceding discussion we can easily infer that the three core objectives of any sensible energy policy nowadays are (1) security of supply, (2) competitiveness, and (3) sustainability. Renewable energy and energy efficiency investments are crucial if we are to make energy supplies more sustainable, competitive and secure. These goals support each other. More sustainable energy sources, such as renewables, help the energy sector to be more competitive, as well as diversifying and securing its energy supply. Yet implementing policies to promote green energy and efficiency is no easy task. This chapter seeks to discuss the difficulties facing the regulation needed in the energy sector and to analyze the key concepts and the main markets failures that characterize the energy markets. It will also review the main policies undertaken at EU level in order to deal with the relations between the energy sector and the problem of climate change. The chapter is structured in five sections. After this brief introduction, Sect. 2 reviews some key concepts and market failures. Section 3 describes the policies to promote green energy and efficiency and Sect. 4 illustrates the difficulties associated to the design of European energy policy. Finally, Sect. 5 draws some conclusions.

2 Some Key Concepts and Market Failures

2.1 Energy Efficiency and Energy Conservation

Energy efficiency is using less energy to provide the same service or providing more services with the same energy. For example, if a consumer replaces a refrigerator or a washing machine with a more energy-efficient model, the new equipment provides the same service, but uses less energy. In this way, promoting energy efficiency programs are considered win-win situations as long as the consumer saves money in her energy bill and environmental damages due to energy use are reduced.

Energy conservation is different to energy efficiency as it means reducing or going without a service to save energy. Driving less is an example of energy conservation while driving the same amount with a lower mileage vehicle is an example of energy efficiency. Energy conservation can take place independently of whether energy efficiency is increasing or not. On the other hand, an increase in energy efficiency does not always imply an increase in energy conservation, as it will depend on the rebound effect as it is explained below.

Energy efficiency is even considered as “one of the large resources” [19] and a “hidden fuel” as long as it can extend energy supplies, increase energy security and lower carbon emissions. According to a recent study [14], in 2011 investments in the energy efficiency market globally were at a similar scale to those in renewable energy or fossil-fuel power generation.

There is a substantial body of literature dealing with the study of how to design the energy policy to achieve an increase in both energy efficiency and energy conservation. Several different instruments have been considered and proposed: fiscal instruments, such as taxes and subsidies, technological innovation programs, energy labels for durable goods, command and control instruments and educational programs. A review of this literature can be found in Jaffe et al. [17], Gillingham et al. [10] and Linares and Labanderia [20].

2.2 The Rebound Effect

Energy efficiency is often said to be the cost-effective way of reducing GHG emissions to combat climate change. However, the impact of energy efficiency on total energy use is controversial as long as an energy efficiency improvement can lead to greater use of the energy efficient device and increased spending on other goods that were previously not affordable. These behavioral or systemic responses to the introduction of new technologies that increase energy efficiency are known as the rebound effect (or take-back effect). A brief history of the rebound effect analysis can be found in Borenstein [5] where the author contributes to the microeconomic literature on the rebound effect and quantifies the rebound effect by decomposing it into substitution and income effects. He concludes that the rebound effect is substantial for the vehicle fuel economy and lighting and if ignored, it would lead to substantial overstatement of energy savings. He also states that as long as the rebound effect reflects the creation of economic value, because consumers are able to re-optimize, given the change in relative prices, it should be celebrated and not regretted. On the other hand, Gillingham et al. [9] point out that the rebound effect is real and it makes energy efficiency policy less effective, but they also say that the rebound effect is usually very small and it should not be used to derail energy-efficiency policies.

2.3 The Energy Efficiency Gap

The energy efficiency gap or energy efficiency paradox measures the extent to which end users underinvest in privately optimal energy efficiency improvement. Therefore, it has to do with the difference between the optimal and the actual levels of energy consumption. It has attracted wide attention among energy policy analysts, as society has forgone the apparent cost-effective investment in energy efficiency even though improvements in efficiency significantly reduce energy consumption at low costs.

Gillingham and Palmer [11] offer a thorough review of the most recent literature relevant to the energy efficiency gap, including the latest insights from behavioral economics. They conclude that engineering studies may overestimate the size of the gap because they fail to account for all costs and neglect particular types of economic behavior. Furthermore, some market failures, which we explain below, such as asymmetric information or agency problems, contribute to the gap. Moreover, they find that the relative contribution of the different factors to the gap depends on the energy user and on the energy use. Therefore, they conclude that this should be taken into account by policymakers when designing cost-effective energy efficiency policies.

In this sense, Allcott and Greenstone [2] argue that policy intervention to reduce the energy efficiency gap should address directly the market failure that causes the gap. For example, if agents are imperfectly informed and the government has an inexpensive information disclosure technology, this is the approach to be used. When the first best policy is not feasible, the use of second best policies, such as energy efficiency standards, should be promoted. Even more, sometimes a combination of instruments may be the optimal policy. This is the result obtained by Tsvetanov and Segerson [28] using a behavioral economic approach to analyze the role of energy efficiency standards. They conclude that in the presence of temptation a policy combining standards with a Pigovian tax can yield higher welfare than a Pigovian tax alone. This means that both instruments should be viewed as complements rather than substitutes.

Using data for the US, and in the presence of misperceptions over energy savings, Parry et al. [25] show that combining carbon pricing with gasoline/electricity taxes is better than combining with energy efficiency standards.

2.4 Market Failures

One of the main contributions of economics in the analysis of energy policies has to do with the concept of "market failure". Energy markets often fail in obtaining efficient results and this is due to the fact that many of the products generated by the energy sector are products, that when used as productive or consumption inputs, generate multiple external effects. In the presence of these negative external effects, private costs are lower than social costs and, as long as this is not taken into account by the markets, it is a source of inefficiencies.

One of the main externalities is the effect derived from the use of fossil fuels and their impact on environmental quality. Climate change is one consequence of this massive use of fossil fuels. Unfortunately, the question about what to do and how to achieve a situation in which there are incentives that work in the direction of using alternative energy sources is full of difficulties not only at the conceptual but also at the practical level.

Environmental effects are not the only effects that have to be taken into account when designing an appropriate regulation. There are distortions that influence the energy sector, some of which are related to questions analyzed in the Principal-Agent literature.[2] This literature, devoted to the analysis of asymmetric information and the problems that it originates, addresses the question of what happens when the Principal (the one that takes economics decisions) does not have all the information that is available to the Agent (the other party) that has to fulfill the contract signed with the Principal. A detailed analysis to quantify the energy efficiency gap due to Principal-Agent problems can be found in IEA [13].

Another important reason for market failures is the existence of transaction costs. Coase [6] was the first economist to analyze the interrelation among the neoclassical

[2] See Laffont and Martimort [18] for a survey of this literature.

theory of markets and transactions costs,[3] Mundaca [22] provides empirical evidence on the nature and scale of transaction costs in energy efficiency projects. He shows that these costs depend on the specific characteristic of each project.

The presence of external effects, asymmetric information and transaction costs are only three of the many factors that make it difficult to achieve efficiency in the energy sector. Other reasons that are also relevant include noncompetitive conditions in energy markets, the need to use the long run perspective or the differences that arise among private and social discount rates.

3 Policies to Promote Green Energy and Efficiency

The difficulties in designing appropriate public regulation in the energy sector may explain why energy policy in many countries has not been able to achieve neither energy conservation nor efficiency in the use and production of this vital input.

The failure of many of the policies implemented is related with the need to conciliate the technological point of view with the economic perspective. There are, for example, optimal options, from a technological point of view, that may not lead to what economists consider an optimal solution, mainly because cost effectiveness is not guaranteed. In other words, the objectives of energy conservation and energy efficiency (defined in the previous section) are, in many occasions, achieved at a cost that is considered too high by economic analysts.

The "technological" point of view suggests that technological progress will be capable of solving the problems that arise in the energy sector and that the achievement of energy efficiency should not be too costly. Nevertheless "too costly" is a vague expression as economic theory shows that public policy has to be able to achieve energy efficiency in a cost-effective way. This implies the selection of policy instruments that are "cost-effective" or equivalently that achieve the objective at minimum costs Baumol and Oates [4].

With respect to the objectives, the fulfillment of social efficiency or the achievement of cost effectiveness should not be confused. Efficiency implies solutions in which externalities are internalized, prices of the goods reflect the social costs of production (not only the private costs) and markets function smoothly so as to achieve efficient allocations of goods and services.

An example will be clarifying. Assume that a given level of mitigation of CO_2 is pursued by means of public intervention. If the instruments used and the way of implementing them are such that the cost of getting the proposed mitigation is minimized, we will say that the solution is a cost minimizing one. We cannot say however, that we have achieved efficiency if we do not know which the efficient levels of mitigation or emissions are. And this is no easy task, as complex models and computations are needed.

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[3] The work by North [23] is also very inspiring.

We should also bear in mind that quantity instruments (command and control policy) do not operate in the same way as price instruments (taxes and subsidies) and both should be carefully designed when energy efficiency and energy conservation are the objectives.

Finally, let us mention some other difficulties. Any energy policy needs a medium and long run perspective and it has to include considerations that go beyond technological and economic ones. Examples include considerations dealing with consumer behavior, education for achieving efficiency in consumption and knowledge about the consumers' discount rates. There is work in progress in these important areas but there are no definite answers for all the questions raised (e.g. [28]).

When considering policy options, technological change and the way in which this change can be pushed in the right direction is another crucial variable. The response of technological change to the development and use of energy sources that result less harmful for the environment is analyzed by Acemoglu et al. [1]. Their work introduces endogenous and directed technical change in a growth model with environmental constraints. Their analysis characterizes dynamic tax policies that achieve sustainable growth or maximize intertemporal welfare. The conclusions obtained in this research depend greatly on whether the inputs used in production, that come from two sectors (a clean and a dirty one) are sufficiently substitutable or not. When there is sufficient substitutability between inputs of production, instruments such as carbon taxes and research subsidies should be a component of energy policy as they can help to achieve sustainable long-run growth. Furthermore, if an exhaustible resource is used in the dirty production sector, the presence of two inputs that are close substitutes will facilitate the switch to clean innovation, without any kind of policy.

These results serve to highlight the importance of the degree of substitution between clean and dirty energy inputs as well as questions on the importance of the exhaustibility of resources. If perfect substitution were a real possibility, policy options would be more easily decided than when this is not the case. Take for example the case of renewable energy that uses clean technologies versus nonrenewable energy (fossil fuels). In this case, certain types of analysis may be misleading if they are based on the assumption that both sources of energy are perfect substitutes. It is clear that in the real world perfect substitution is not the correct assumption as renewable energy cannot be stored. Unfortunately, some policy measures have been adopted without taking into account these two facts and may explain some of the policy failures.

Another important question for energy policy has to do with difficulties that appear when the policy maker tries to influence the path of technological change using different instruments at hand. As we mentioned earlier, this objective is difficult and complex and confronts much uncertainty as to whether the main influence of technological change takes place in the longer term. This uncertainty about long-term consequences contributes to the difficulty for agreeing on energy policy.

The Japanese government's decision of engaging in a long-term policy of substitution of all kind of nuclear energy for energy obtained with other technologies, as a consequence of the Fukushima accident in 2011, constitutes an example of these changes. The uncertainty about future events and the large damages are compelling reasons for the Japanese government that has decided to use the precautionary principle as a basis for energy policy. This has been something inevitable and demanded by citizens.

There are also other examples (the Germany's nuclear phase-out policy, for instance) in which energy policies have changed in a quite a drastic way. The reduction of the subsidies to renewable energies is also very illustrative. Some governments have decided that the amount needed to maintain the renewable energy alternative is too expensive as to be sustainable and have decided, as in Spain, to change its policy regarding subsidies, which has generated uncertainties and losses to many investors in the sector. This change has confused the energy sector and investment in renewables, in particular solar energy, is experiencing an important decline. This constitutes an example in which energy policy is subject to uncertainties that lead to unexpected changes because the objective, an increase in the renewable share in the energy mix, has resulted to be more expensive than was planned.

Finally let us note that, as the implications of energy use affect many countries and regions, there is a need for good energy efficiency indicators.[4] Without them, it is impossible to have consistent and comparable evaluations of energy efficiency situations in different countries. These comparisons are needed when negotiations, regarding the issue about which is the best way to curb GHG emissions, take place between different parties.

Fortunately, not every aspect of energy policies is subject to uncertainties. There are also issues for which some sort of consensus exists and provide some certainties on which to base energy policy. For example, Jaffe et al. [17] argue that when subsidies and tax credits are the instruments used to achieve energy efficiency, consumers that may have purchased an efficient product even in the absence of the subsidy, might receive public money. Consequently, it may be better to design policies that increase energy prices and diminish the cost of technological alternatives generated through innovation. This combination may be effective to promote the use of more energy efficient technologies. The existence of behavioral barriers also suggests the need to take a different route on some policies. Putting the attention in factors such as consumers' education is one of these different routes.

In the past few decades a number of different instruments have been used to promote energy efficiency: taxes, market for permits of CO_2 emissions, subsidies, tax credits and technological innovation. As in other areas of environmental economics, the analysis of whether or not command and control policies in the form of

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[4] Fortunately, recent advances are being made to provide good energy efficiency indicators by the World Energy Council or the International Energy Agency at the world level and by the ODYSSE-MURE Project and Fundación Repsol at the European level.

energy efficiency standards are a good choice for public policy has raised a great deal of attention. Parry et al. [25], using an analytical framework that is parameterized with US data, conclude that pricing policy is of crucial importance, although this does not mean that efficiency standards should be negatively classified as there are many arguments that work in favor of standards. This is so when it is crystal clear that pricing policies may not be credible in cases in which the government commits to maintaining those policies far into the future. Yet, having said this, it is also necessary to remember that if efficiency standards are used they should be imposed in particularly chosen sectors and implemented in ways that guarantee costs effectiveness.

The conclusion that energy efficiency standards and Pigouvian taxes need not be substitutes but should be viewed as complements is made by Tsvetanov and Segerson [28] in a context in which consumers do not behave in the traditional rational way that neoclassical economic models assume. Instead a behavioral approach where consumers may be "tempted" to buy cheap and inefficient goods may be a possibility even though that kind of behavior is not rational.

4 Energy Policy in Europe: An Example of the Difficulties

The EU has a full range of objectives and policies that either have significant climate change co-benefits or aim at directly tackling climate change. However, as the report by Hohne et al. [12] shows, there is an overlap among the targets of the EU Climate and Energy Package, and emissions from some sectors are covered by a number of targets, which makes energy policy very complicated.

Consider, for example, some emissions from industry that are covered by the EU ETS, renewables, energy efficiency and Kyoto Protocol targets. If we concentrate in the energy efficiency target, we find the following plans and actions: (i) The 2005 Green Paper on energy efficiency (planned to reduce energy consumption by 20 %, compared to Business as Usual) and (ii) the 2006 Action Plan included as part of the EU's Climate and Energy Package in 2008/2009 (adopted in June 2010 as part of the new Europe 2020'strategy).

The energy efficiency target was again confirmed on February 2011 at the Transport, Telecommunications and Energy Council Meeting and the instruments used in Europe for this policy have been the following: (a) access to finance, (b) availability of innovative products and (c) incentives to induce energy-efficiency investments and the use of EU structural funds. Given that the target can be subdivided in many others sub-targets it is difficult to know whether or not there are too many instruments for only one target.

Three other Directives concerning the achievement of energy efficiency are: (i) the Eco-design Directive (2009), that requires producers to make reductions in energy use and other environmental impacts an integral part of the design process of electrical appliances, (ii) the Energy Labelling Directive (92/75) that constitutes the framework for implementation of Directives for seven household appliance groups and (iii) the Directive on the promotion of cogeneration based on a useful heat demand (2004/2008 CHP Directive).

All these policy initiatives do not, however, take place with a medium and long term planning even though we have argued that this should be the way to proceed. Policy makers should try to decide what are the measures and the periods of time needed to achieve energy efficiency at minimum costs.

As regards the emissions reduction target, the primary tool continues to be the ETS but some changes in the cap will be needed for the above policy instruments to progress. Europe has not forgotten the carbon tax although there are still questions about whether a single carbon tax would be capable of helping to move forward in the fulfillment of the objectives. In this respect, the positions in the theoretical literature diverge.

There are more examples that illustrate the difficulties for achieving good regulation in the energy sector concerning the improvement of the environment. In 2001, the Renewable Energy Target (RET) was approved as a means to mitigate the change in climate. This policy measure has survived since then, although the EU is now considering scraping the use of binding renewable energy targets as part of its global climate change policy mix. It now appears that the European Commission may drop specific binding constraints on the share of electricity generated from renewables [27]. Stavins argues that this potential decision by the European Commission will be good news, not only for the economy but also for the environment. His reasoning relies on the fact that in the presence of the EU ETS, the "complementary" renewable mandate enters into conflict with other policies. He believes that "without the renewables mandate, the cap being planned for the EU ETS will be achieved at lower cost and will foster greater incentives for climate-friendly technological change".

Stavins' arguments rely on the perverse interactions between the three targets (20-20-20) related policies. These interactions are justified on the following grounds. As we know, economic theory shows that quantity restrictions as well as taxes, if they are well calculated, can achieve the proposed targets at minimum costs. Hence, the EU-ETS, with a binding cap, will provide the necessary incentives for minimum abatement costs. If regulators introduce another additional measure, two possibilities arise. The additional measure may be either irrelevant or it may generate inefficiencies. For example, it may generate excessive abatement in the electricity sector in relation to what it would be cost-effective.

Furthermore, technological change may be retarded if the price of the permits in the market is reduced, something that can be considered as a real possibility.

The relation between the energy sector and Climate Change is one of the reasons that explain why regulation and policies to internalize this type of external effects have been so closely analyzed. After all, Climate Change Policy is a priority for the governments of many countries.

5 Conclusions

The development and progress of the world depends on energy in its different forms. Hence, in order to analyze the problems that the generation of energy, as well as it use originates, it is imperative to have a long term perspective in which to include conditions related to the role of the sector as a basis for economic and social progress as well as conditions related to the security of provision. Countries and their economies require, if they do not have property rights over energy resources, reliable and durable energy sources to be ensured. This explains why energy resources are not only a source of wealth but also a source of tension at world level.

The energy sector provides important services such as electricity, a fundamental input, which if available at “reasonable prices”, ensures competitiveness for economic activities and consumer’s well-being. Yet the technology used and the activities undertaken in this sector generates multiple externalities and local and global environmental damages. Therefore, a well-implemented public regulation is needed to guarantee that “environmental friendly” technologies are being used together with the fulfillment of the security in provision.

General difficulties for regulation of the energy sector stem from the fact that this is a sector that needs a medium and long term perspective. And this is so because technological changes exert their influence over the sector in the long run. Yet knowledge about how technological changes influence the energy sector in the long run is not easy to anticipate. In fact, technology and its development is a complex business full of uncertainty.

Furthermore, the energy sector needs, more urgently than other productive sectors, large investments. A long term view is again needed as regulation cannot miss the point of looking at the future before taking any decision. The short run perspective leads to mistakes when planning how and what to do with energy, how to regulate and the way in which energy is used. The necessary horizon for dealing with energy problems is the long run and the future is, most of the time, full of uncertainties.

On the other hand, the differences between the technological perspective and the economic perspective have to be borne in mind as public policy in the energy sector may sometimes pursue objectives, such as energy efficiency or economic efficiency, that need different measures and different instruments.

The difference between these two concepts implies that the policies adopted and the instruments chosen have to fulfill the conditions of being “cost-effective”. Only with this premise would it be possible to obtain the results that will maximize collective welfare.

In general, when evaluating the costs that changes in the energy sector would generate, economists tend to be more pessimistic than engineers. We are aware that the changes needed in the energy sector are a difficult task given the cost-effectiveness condition. However knowledge is improving and we should be confident in the future. It is a difficult but not an impossible task.

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EU Policies and Regulation on CO_2, Renewables and Energy Efficiency: A Critical Assessment of Recent Experiences

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Abstract For over 20 years, the EU has taken on a clear role of international leadership in energy and environmental policy, with a strong commitment to bringing down CO_2 emissions, promoting renewable energies and enhancing energy efficiency. Regulatory experience has been very varied, with several different kinds of regulatory, fiscal and command-and-control instruments, etc. being implemented. The analysis conducted in this chapter shows that there have been "lights and shadows" but it can be concluded that, in general, priority has been given to meeting targets rather than to economic efficiency considerations. Two main tools have been used to bring down CO_2 emissions at EU level: the EU ETS and taxation. On the first issue, our main conclusion is that despite the fact that CO_2 goals have been achieved, the role of CO_2 prices as a low-carbon investment driver has been of relatively little importance. In relation to the second issue, the need to analyse energy and environmental taxation from a broad conceptual perspective, including the extraordinary costs derived from energy, environmental and social policy decisions needs to be highlighted. In the Spanish context, an environmental tax reform needs to be undertaken to address the challenges faced by the energy model: strong incentives are required in favour of technologies which are more efficient and which have lower environmental impacts. In relation to renewables, experience shows good and bad points in each of the supporting frameworks and the general conclusion is that these frameworks should also take into account the characteristics of each technology (particularly its competitiveness). Energy efficiency should be one of the cornerstones for attaining EU energy and environmental goals. Price instruments, standards and information instruments are very useful in overcoming the "energy efficiency gap". In this regard, the Directive on Energy Efficiency will establish the policy framework for the medium/long term.

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1 Introduction

This chapter aims to analyse the main energy and environmental policies at European level, and the way in which these policies are interlinked. It also looks at the targets set and the regulatory instruments in place to attain them. The idea is to draw conclusions that may be of assistance in improving energy policy going forward. This is particularly important in the current scenario, in which the EU is reviewing the framework of targets and instruments for its long-term energy policy. This review commenced at the time of the launch of the Green Paper "A 2030 framework for climate and energy policies", in which the European Commission asks stakeholders questions in order to gather their opinions and future proposals on the European energy model, and continued with the Communication adopted on 22 January 2014 and presented in Brussels by the Commission President jointly with the European Commissioners for Climate Action and for Energy.

Energy policy may be defined as the set of goals, targets and tools that determine the role to be played by energy in society. In this policy framework, regulatory instruments are the tools defined by the regulator with a view to effectively reaching the targets set. In recent years, the regulatory framework for energy and environmental affairs in Europe has been defined by what are referred to as the 20–20–20 targets, to be attained by the year 2020, as follows:[1]

- A 20 % reduction in greenhouse gas (GHG) emissions from 1990 levels.
- Raising the share of final energy consumption supplied by renewable resources to 20 %; including raising the use of renewable energies in the transport sector to 10 %.
- 20 % improvement in primary energy consumption compared to the baseline scenario, via energy efficiency.

In order to achieve these goals, on the one hand various European Directives have been passed[2] , and on the other the Member States have developed regulatory instruments at internal level and to transpose the relevant EU Directives.

As regards instruments aimed at reducing **emissions**, our analysis needs to differentiate between two main groups: first the industrial and energy sectors subject to the European Emission Trading System (EU ETS), which sets a cap on emissions in Europe and lays out a roadmap for meeting those targets by 2020; and then what are referred to as the "diffuse sectors" (transport, R&D&I, etc.). In the latter case,

[1] On 22 January 2014, the European Commission presented a new framework of goals for 2030 at EU level: a 40 % reduction of greenhouse gas emissions from 1990 levels and a 27 % share of EU energy consumption for renewable energy.

[2] The Emissions Trading Directive [5] (2003/87/EC), as amended by Directive [6] 2009/29/EC, the Directive on the Promotion of the Use of Energy from Renewable Sources (2009) (2009/28/EC) and the recently passed Energy Efficiency Directive [7] (2012/27/EU).

the Member States have specific targets for reducing emissions and may on a discretionary basis define whatever policies and instruments they wish to implement to achieve those outcomes.

As the EU ETS has been in operation for some years now, conclusions may be drawn as to its effectiveness and efficiency and proposals for improvement may be made. The same is true of the strategies adopted to reduce emissions in the diffuse sectors, among which taxation has played a key role.

Support for the development and roll-out of **renewable energies** has been organised mainly at national level. However, targets and basic regulations have been defined at European level. These targets are allocated to countries according to the potential for developing renewables and the wealth of each country. The Member States were given total discretion to define the supporting frameworks to be implemented in order to meet their national targets for renewable energies. European experience in this area enables the degree to which targets have been met to be pinpointed, along with the level of efficiency of the instruments and the consequences arising from the mistakes made.

Unlike the two previous cases, the 2020 **energy efficiency** target was not defined on a binding basis. This is another indication of the role to which targets and regulatory instruments for improving energy efficiency have been relegated. Despite the fact that various regulations have been passed in the field of energy efficiency, this aspect has not traditionally been given the same political importance as reducing emissions or promoting renewable energies. In fact, it may be said to be one of the issues that remain pending in European energy policy.

There are significant differences in the regulatory instruments applied by the various Member States, although the drafting of standards for equipment and processes and the adoption of plans to upgrade equipment have been widely implemented throughout Europe.

The Energy Efficiency Directive passed in October 2012 specifies binding energy efficiency targets and a broad range of regulatory instruments that will form the foundations for the energy efficiency regulations in the Member States by 2020. The drafting of this Directive was surrounded by animated debate, reflecting the different opinions of the various Member States in relation to the level of efficiency and effectiveness of each regulatory instrument. These discrepancies were particularly strong in the case of quantity instruments (energy-saving targets for suppliers), which have been in place for several years in some countries but for which no accurate diagnosis is yet available.

The lessons learned from the rights and wrongs of the existing regulatory frameworks are very useful in a context such as the present scenario of debate on the essential aspects of the targets, policies and regulatory instruments beyond the 2020 horizon, in a situation of economic crisis with extreme pressure to improve competitiveness and drive economic growth.

In this regard, the European Union has already started work by proposing the Energy Roadmap 2050,[3] which is considered as a point of departure for advancing towards a sustainable energy model. In this document, Europe aims to reduce GHG emission levels by 85–90 % from 1990 levels.

This chapter comprises an introduction and sections on five main aspects of energy policy:

- The second section is devoted to policies designed to bring down CO_2 emissions, focussing on the EU ETS.
- The third section looks at the environmental and energy tax framework in Europe.
- The fourth section addresses the frameworks in place for supporting renewable energies.
- The fifth explores regulations to promote energy efficiency.
- The last section summarises main conclusions of the previous sections.

2 Analysis of the Main European Regulatory Instruments on Energy Issues

2.1 Description of the EU ETS

The European Council of March 2007 set a target of reducing EU GHG emissions by 20 % from 1990 levels by 2020, i.e. a 14 % reduction on 2005 levels. This was to be split between the sectors subject to emissions trading,[4] which committed to a 21 % reduction target, and the remaining sectors (also referred to as "diffuse" sectors) for which the target was 10 % at European level. In this case, a Decision[5] by the European Commission allocated the targets to Member States according to the Gross Domestic Product (GDP) of each one.

In industry the key regulatory instrument for reducing emissions is the EU ETS, which was set up in 2005 under the terms of the Emissions Trading Directive [5] (2003/87/EC).

This first Directive laid the foundations for emissions trading, defining the basic emissions limits authorised in order to create scarcity, defining what activities were

[3] This document is under review because many of the economic and technological scenarios described are now out of date and probably no longer apply.

[4] This framework includes energy generation industries and industrial sectors with a high level of energy consumption, e.g. power plants over 20 MW, hydrocarbon refineries, coke ovens, steel production facilities, cement production facilities, paper manufacture operations, glass manufacture operations, ceramics plants, etc.

[5] Decision 406/2009/EC of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020.

included in the scheme, establishing the methodology for allocating emissions and leveraging the possibilities for flexibility afforded by the clean development and joint implementation mechanisms (CDM and JIM, respectively) created by the Kyoto Protocol.

Basically, companies received emissions allowances free of charge under national allocation plans (NAPs), which were designed by national authorities on the basis of the emission reduction ceilings set by governments at national level and the prospects for development over time in each particular sector and installation. At the end of the year, each company then had to submit to the relevant administrative authority emissions allowances equivalent to the volume of CO_2 emissions (in tonnes) released into the atmosphere.

The experience gained by the European Commission in the early years of the EU ETS was taken into account when drafting Directive [6] 2009/29/EC, of 23 April 2009, so as to improve and extend the GHG emissions scheme of the Community. One significant change was the fact that a European emissions ceiling was defined and a centralised emissions allowance allocation system was set up with the same norms applying throughout Europe. Under the new scheme, the auctioning of allowances was established as the basic methodology for allocation in the electricity sector, with some exceptions being made in the case of certain particular circumstances, mostly affecting former Eastern Bloc countries.

In short, Directive [6] 2009/29/EC constitutes the basic framework for regulating the trading of GHG emissions allowances from 2013 onwards (referred to as Phase III). Some of the main changes are as follows:

- The allocation of emissions allowances to all of the installations included in the scheme is centralised at European level (European ceiling) and binding target quotas are set at national level. As mentioned previously, this allocation is generally carried out by means of an auction.
- Allocation free of charge is only envisaged in production sectors at risk of "carbon leakage" (i.e. at risk of relocation outside the EU).
- The possibility is also envisaged of an activity with intensive electricity consumption being affected by carbon leakage as a result of electricity becoming more expensive due to the implementation of the emissions allowance trading scheme.
- For efficiency reasons, Member States are allowed to exclude small installations from the EU ETS.
- The use of allowances derived from the use of mechanisms linked to project development under the terms of the Kyoto Protocol—i.e. JIM and the CDM—is limited in accordance with the principle of complementarity: the total volume may not exceed 50 % of the reduction.
- 5 % of the total allowances is reserved for "new entrants". 2 % of this amount must be allocated to fund pilot projects involving generation from renewable energy sources and carbon capture and storage.

The years since the launch of the climate change package (understood to mean the emissions reduction targets for 2020, the EU ETS and the Decision with country-allocated targets for diffuse sectors) have revealed two fundamental issues.

First of all, the EU ETS has proven to be effective in bringing down emissions, thanks to the structure of the regulatory instrument ("cap and trade"). However, the economic crisis and its consequences for production and demand in the economy have resulted in the prices per tonne of CO_2 plummeting and thus weakened one of the main drivers envisaged by the regulator: a technological shift towards a low-carbon economy, which is the second main goal (albeit implicit) for which this framework was defined.

The second fundamental issue is the difficulty of achieving reductions in emissions in the diffuse sectors, particularly in transport and building. In these sectors, the lack of concrete commitments by stakeholders and the technological difficulties in introducing low-carbon technologies jeopardise progress towards the decarbonisation of the economy beyond the 2020 horizon.

An analysis focussed on emissions allowance trading shows that the basic characteristic of the end of the previous stage (2008–2012) and beginning of this third stage is a slump in the price of CO_2 emissions allowances, as a result of the major economic crisis, which has reduced industrial activity and the demand for allowances. This is further compounded by the increasing penetration of renewables as a result of specific support schemes (Fig. 1).

Despite the fact that the emissions allowance market is working smoothly (bear in mind that the emissions target is being met and that the price is in keeping with the basic factors), many analysts claim that the price of CO_2 in the European market has fallen so low, and at the same time shown such a high level of volatility, that it is no longer providing an incentive for the investments required to decarbonise the economy (since January 2013, the price of the EUA has remained below €5/tonne CO_2). In fact, without the banking effect (i.e. companies with the highest emissions taking advantage of the current low prices to buy allowances as an optional hedging mechanism in case CO_2 prices soar after 2020 for any reason), the price of CO_2 might well have dropped to almost zero.

In the light of this situation, in July 2012 the Commission published a draft for the amendment of the auctioning rules for the EU ETS, according to which the allocation of a particular number of emissions allowances would be postponed. To be more specific, the Commission proposed reducing the number of emissions allowances to be auctioned between 2013 and 2015 by 900 million and increasing by the same amount the volume auctioned at the end of the third stage (this is referred to as "backloading" in EU jargon).

By implementing this postponement strategy (which basically means changing the slope of the curve for maximum emissions allowed in the early years at the expense of increasing the maximum emissions allowed at the end of the period), the European Commission seeks to restrict the offering of emissions allowances in short-term auctions, thus raising the short-term price. It will then offer more allowances at the end of the period, when demand is expected to have recovered.

Fig. 1 EUA (Emission Unit Allowance) prices in the European market *Source* Bloomberg

Assuming that the effect of this increase in emissions as a result of backloading at the end of the period will be more than offset by the aforementioned increase in demand, the CO_2 price will go up. It is, therefore, a measure basically intended to reduce the volatility affecting the price of allowances, and thus reduces the risk perceived by potential investors.

This backloading proposalwas adopted in February 2014.

2.2 Proposals

With a view to strengthening the CO_2 signal price as a driver for decarbonising the economy and reinforcing effectiveness and efficiency in bringing down emissions, two kinds of measures are possible: structural and cyclical.

These measures should also ensure a certain CO_2 price level and stability, in order to achieve the volume of investment that is needed to attain the targets specified.

- Structural measures. These measures will help consolidate the improvements introduced since the EU ETS began and lay the foundations for reducing emissions in the long term. Some of the main measures are summarised below:
  - Set post-2020–2030 targets at the earliest possible opportunity to provide certainty to investments and increase current CO_2 prices through banking. This intervention will unilaterally increase carbon and energy prices to 2020, but there is unlikely to be a significant impact on investment decisions without visibility of the longer term carbon price.

 - Bring forward the announcement of the widening of EU ETS sector coverage, raising the CO2 price through banking leverage. It would be sensible to extend the scope of the EU ETS to other sectors including economy-wide fuel consumption. This extension will improve the efficiency of the scheme, as an efficient market mechanism is applied to more sectors in the economy. Applying the EU ETS only to industrial sectors leaves a very important part of the economy out of the effort for efficient emission reduction. This measure could avoid the promotion of expensive emission reductions in current non-EU ETS sectors while less expensive reductions are available in the EU ETS sectors (or vice versa).
 - If the EU ETS is to be extended to all end consumers of fuel, it is important to coordinate these measures with fuel tax measures in order for the combination and interaction of each measure to reflect the external cost.
 - Set additional limitations on the use of international credits in the EU ETS.

- Cyclical measures for rapid implementation, such as the backloading proposal. We do not believe that backloading will be an added handicap to the competitiveness of European industry if the necessary additional measures to preserve that competitiveness are adopted, e.g. strengthening the support measures that are already set under existing EU State Aid Guidelines which allow compensation for ETS-related increases in electricity prices to prevent the risk of carbon leakage.

3 Environmental and Energy Taxation

3.1 Description of the European Framework on Environmental and Energy Taxation

'Environmental taxation' is understood to mean a form of taxation that internalises an environmental cost that is reflected in the price of the manufactured good; a theoretical framework has been developed around this concept.[6] However, in defining this term it must be remembered that there is an ongoing debate as to what exactly an environmental tax is, or should be, and whether the tax should seek to internalise the environmental cost incurred or alter the behaviour of the stakeholders.[7]

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[6] See, for example, OECD [25]. *Environmentally Related Taxes in OECD Countries. Issues and Strategies*, Chap. 1.

[7] For an argument in favour of the need for the tax to alter behaviour, see Joskow (1992), p. 54, for example.

In analysing European experiences in the field of environmental taxation, OECD reports are very useful[8] as they take a broad statistical basis into account and carry out a thorough review of both academic literature and the legislation in force.

An analysis of a significant number of OECD publications on energy and environmental taxation, as well as of the statistics drawn up by the OECD in this field ,[9] leads to at least two significant conclusions.

First, the indicators used to compare the burden of environmental taxation in different countries should be carefully scrutinised, as in many cases they may be dependent on final energy consumption trends, how consumption is structured or how taxes are designed. For example, the overall revenue value of an *ad valorem* tax (e.g. the tax on electricity in Spain) is not as dependent on energy consumption trends as a tax levied at a rate based on units of energy (e.g. liquid hydrocarbons in transport).

Second, an analysis of energy and environmental taxation should be supplemented by the introduction of regulatory concepts that impose charges on energy consumers in order to finance energy-related, environmental or social policies. This is the case, for example, of the costs incurred by electricity consumers in order to finance the meeting of the renewable energies target in many European countries, i.e. a public policy target that is derived from European regulations.

In October 2003, the European Commission passed Directive [5] 2003/96/EC on energy taxation, which came into force on 1 January 2004. This Directive sets the minimum levels of taxation applicable to energy products intended for the production of motor and heating fuels, as well as for the production of electricity, although in the latter case the Member States may introduce exemptions on a discretionary basis. They may also apply exemptions to biofuels, among others, and to special sectors. The Directive acknowledges the political and structural particularities of each Member State, meaning that there are also exceptions for specific cases.

The tax base, according to Directive [5] 2003/96/EC, is the volume consumed in the case of petroleum-based products, and the energy content is the case of coal, gas and electricity.

Some dysfunctions were detected in this system. For example, there is no clear price signal for CO_2 emissions or energy content; nor are there sufficiently strong incentives for the development and use of alternative energies. There is also double taxation in the case of the industries that are subject to the European emissions trading market. In view of this, the European Commission issued a draft Directive in 2011 for which the appraisal process is still open.

In order to correct the inefficiencies found in the previous Directive, the most important addition in the new proposal is to divide the energy tax into two parts: one based on CO_2 emission levels and the other on energy content, both of which are to be equally applied to all energy products (apart from some exceptional cases).

[8] The following reports are of particular interest: (1) OECD [23] Environmentally Related Taxes in OECD Countries. Issues and Strategies. Paris; and (2) OECD [24] Taxing Energy Use. A Graphical Analysis, Paris.

[9] OECD [24] Taxing Energy Use. A Graphical Analysis, Paris.

This separation implies that energy products with zero emissions will be exempt from paying the tax, which therefore provides an incentive for alternative energies. On the other hand, a tax on energy content creates a clear signal in favour of saving energy.

The new proposal also includes the gradual phasing-out of subsidies that are not justified from an environmental viewpoint, and does away with the double taxation in the case of the EU ETS mentioned above. It also includes a gradual increase until 2018 in all the minimum tax levels already described in the current Directive, through most of the exemptions, reductions and exceptions contemplated in the 2003 Directive for special sectors (e.g. agriculture) and specific national or regional situations are maintained.

Total environmental taxes in the European Union currently account for between 2 % and 3 % of the GDP of Member States, peaking at 4 % in Denmark and Holland (followed by 3.4 % in Slovenia). In the case of Spain, France, Lithuania, Romania and Slovakia, however, they remain below 2 %.[10] Energy taxes account for most of this amount, but there are broad-ranging differences between countries, as shown in the bar chart below. Denmark, Luxembourg[11] and some of the new Member States[12] have the highest tax revenue. The countries with the lowest income from energy taxes are Belgium, France, Ireland and, in last place, Spain. In any case, it is important to note that in the case of the new Member States the high tax revenue is not so much because of high taxation levels but rather because of their high energy consumption. Thus, in a comparison of two countries with the same GDPs but different levels of energy intensity the one with the higher intensity would have a higher revenue/GDP ratio than the other, even if the latter has been making more efficient use of its energy (Fig. 2).

The bar chart above also reveals that transport appears to be subject to a considerably higher tax burden than other energy sectors. This disparity is clearly explained in the next section.

3.2 *Proposals: Sending the Right Signal on an Economy-Wide Basis*

3.2.1 The Need for a Sectoral Approach

It is highly complex to analyse energy and environmental taxation on a sectoral basis in a group of countries as broad and heterogeneous as those of the EU. Oversimplification could distort the general conclusions regarding the fiscal pressure to which consumers in each sector are subject.

[10] Eurostat (2013), p. 41.

[11] However, as explained in OECD [24], Luxembourg is biased in this regard because of its high revenues from fuels for cars to be supplied to many non-residents.

[12] Extensions from 2004 and 2007.

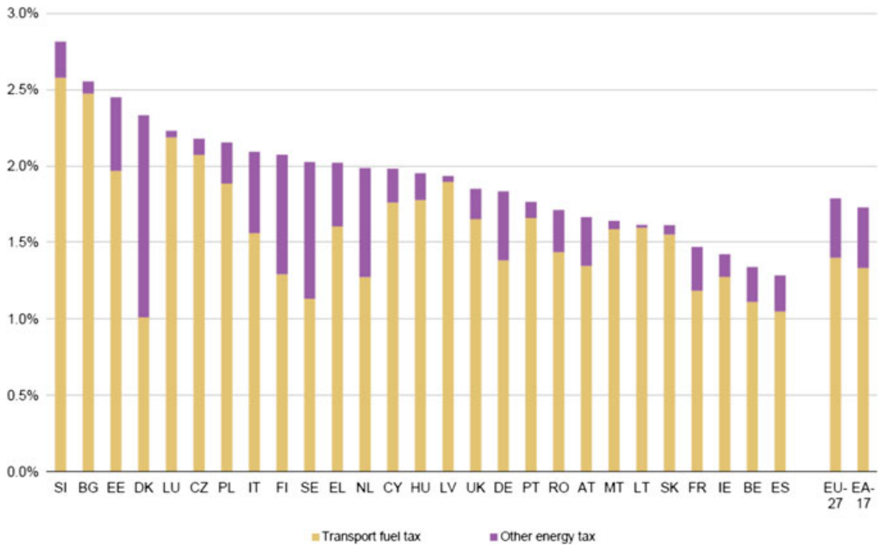

Fig. 2 Energy tax collection per Member State in 2011, expressed as % of GDP

This section sets out to draw some general conclusions on the basis of the ideas expressed in some recent OECD reports on energy taxation[13] and our own analysis based on experience in energy and environmental policy in the EU. To complement these conclusions, we mention various issues that should be taken into account when exploring how each sector contributes to the funding of energy and environment policies.

The report *Taxing Energy Use* (published by the OECD in January 2013) analyses for the OECD as a whole and for each member country how energy taxation is structured for three major sectors: transport, heating and electricity. The general conclusion is that of the three, the transport sector pays most taxes. This is confirmed both when analysing the information provided by the countries and when grouping their information together in the form of simple and weighted averages for the OECD as a whole. However, after this conclusion, the report also includes a significant number of very interesting additional reflections. We now sum up some of the main issues mentioned in the report in this regard, as well as some of our own ideas.

First of all, on the basis of the explanations provided in the report, it can be concluded that just because transport is affected by more taxes than other sectors, that does not mean that it is the sector that bears the highest energy or environmental tax burden. This is confirmed by the fact that the information from the sample of countries under consideration reveals that the tax rates established for transport address external issues that go beyond the energy or environmental

[13] OECD [23, 24].

sectors. For example, they address aspects such as congestion, public health problems derived from traffic accidents, problems associated with noise levels, etc. Moreover, the report indicates that most countries do not have an adequate framework for sharing out road use costs among users ("road pricing"), which means that governments have the incentive of using fuel consumption ("road fuel consumption") as a proxy for setting tax rates and thereby funding the costs of transport infrastructures (e.g. road construction and maintenance). In other words, most of the tax on transport is levied with the goal of funding transport infrastructures (although this is not the only goal pursued: as mentioned above, the tax collection goal plays an important role in energy taxation), i.e. for a purpose entirely different from energy and environmental policy.

One important indication of the lack of sustainability of the transport sector in the OECD countries is the rising trend in CO_2 emissions, which is often one of the factors that most hinder the emission reduction commitments undertaken by countries. Obviously, the tax on fuel used in transport is a major environmental signal. However, the fact that its origin, design and motivations fall entirely outside this scope mean that it is not often used to address the challenges faced in this sector.

Secondly, apart from the taxes in other sectors, such as electricity, consumers commit to costs, make contributions, and are even asked to provide funds with a view to funding compliance with environmental or energy targets set by governments. This phenomenon is can be clearly seen in the case of the European Union, where the electricity sector is subject to the EU ETS. Under this scheme, stakeholders have targets for bringing down emissions and incur a cost for every tonne of CO_2 that they emit in the electricity production process, which is then reflected in the market price for CO_2 emission allowances. This cost, which is not taken into account when calculating the energy or environmental taxation borne by electricity consumers, is equivalent to a tax on CO_2, which is not applied to the transport sector in the case of the EU. In addition to the cost of CO_2, as evidenced in the case of Spain, electricity consumers often fund most of the development of renewable energies with resources collected from their electricity tariffs.

Box 1. Quantitative analysis for Spain to illustrate the differences between the electricity and transport sectors as regards fiscal pressure and charges derived from energy and environmental policy

In Spain, the access tariffs payable by electricity consumers are used to fund many items not strictly linked to the power supply and which contribute to financing environmental or social policies (for example, premiums for renewable energies or support for domestic coal). To simplify our analysis, non-mainland compensation costs (paid by electricity consumers to compensate for the extraordinary cost that would apply to consumers for supplying electricity to island territories) and interruptibility costs are not included.

As well as the above, the price of electricity includes the cost of regulatory decisions that have given the electricity sector a special role in the

decarbonisation of the economy. A case in point is the cost of CO_2 emission allowances, to which the electricity sector is subject due to its inclusion in the EU ETS. It is obliged to reduce emissions and incurs a cost for every tonne of CO_2. In order to quantify this impact, the price of CO_2 futures and their repercussion on the market price are taken into account. Another energy and taxation policy decision that has an impact on the price of electricity is Act 15/2012 of 27 December on tax measures for energy sustainability, which introduces charges and fees that increase the cost of the technologies used for electricity generation. Although the exact extent of this impact is not yet known, a significant portion of the cost of these new tax rates will be internalised in the price of electricity in the wholesale market. As a conservative estimate, an increase in the whole market price of electricity of €5/MWh can be expected.
In analysing the hydrocarbons used in the transport sector[14] VAT, the special tax on hydrocarbons and the cost incurred by the sector for mixing biofuels are all taken into account. As regards income, it is assumed that there is an informal subsidy (net income), as the revenue from road and registration tax does not cover the total cost of infrastructures (which it should in theory cover), and there is no other tax whereby drivers take on this cost.
In view of the foregoing, the costs in Euros per gigajoule would be approximately as follows (Fig. 3):
The figures in the above table sum up most of the ideas set out in this chapter. Thus, by analysing energy and environmental taxation from a broad conceptual perspective—including the extraordinary costs derived from energy, environmental or social decisions—it is proved that electricity consumers (taking into account the aforementioned adjustments) pay for each unit of energy consumed almost three times more in charges that are unrelated to supply (€19.18/GJ) than consumers of petrol/gas-oil (€6.56/GJ) do.

Finally, most comparative analyses of energy and environmental taxation in different countries do not include regional taxes (e.g. *Taxing Energy Use*). This leaves out most of the fiscal pressure in countries with highly decentralised administrative structures, such as the US, Germany or Spain. In the latter country, exponential growth in new environmental taxes on electricity facilities and generation is a highly significant phenomenon.

The complementary analysis proposed in this section of the link between energy taxation applied to each sector and its economic contribution to meeting energy and environmental policy targets is completed with a numerical analysis in the section devoted to Spain. It combines the tax burden on each sector and its economic contribution via regulatory instruments (such as the CO_2 market, support frameworks

[14] This is simplified by considering petrol and gas–oil consumption.

€/GJ	Electricity	Petrol/gas-oil
VAT	7.70	6.65
Other taxes[a]	1.78	9.20
Other costs[b]	16.84	0.21
Other income	-7.14	-9.50
TOTAL	**19.18**	**6.56**

Fig. 3 Estimated extraordinary costs in electricity and transport sectors. **a** This includes tax on electricity in the case of the electricity sector and the special tax on hydrocarbons in the transport sector, **b** Costs not associated with electricity supply (premiums for renewables, etc.) and costs of biofuel mixture allowances for the transport sector

in place for renewable energies, pseudo-environmental taxes established by regions, etc.) to set up a level playing-field that enables the environmental burden on each sector to be determined.

3.2.2 Progress Towards a European Tax Reform to Include the Principles of Reform Raised in the Draft Directive: The Case of Spain

The impact assessment accompanying the proposal for a revised Directive, drawn up by the European Commission, acknowledges the need for tax harmonisation at European level to prevent distortion of the internal market due to the current situation with so many different taxes and concepts in each Member State. At national level there is a similar problem, leading to a scenario that might be described as "pseudo-environmental taxation".

Moreover, at state level there are few taxes that may be considered to be genuinely linked to the environment or to include the environment as a variable in any way. Corporation Tax, for example, provides for deductions in the case of investments that may be considered to be made in the environment, but beyond that these taxes are normally applied to the energy sector (transport and electricity). Therefore the transport sector is affected by various taxes that are sometimes at odds with environmental logic: for example, the Spanish IVMDH tax[15] is levied on bioethanol and biodiesel, both of which are renewable, but not on natural gas or LPG (liquid petroleum gas).

On the other hand, Spain's Autonomous Regions have compensated for the void in state-level environmental taxation: hence, most environmental taxes apply at regional and not at central government level [10]. However, regional taxes on the energy sector, and in particular on the electricity sector, have traditionally been based on a presumed environmental goal with the intention of increasing revenue from the regions. This category includes many charges and fees that are widely heterogeneous and geographically distant within the State. They mostly apply to electricity generation and distribution grids.

[15] Tax on the Retail Sale of Certain Hydrocarbons.

Fig. 4 Charges in the various Autonomous Regions. *Source*: own records

The lack of any true environmental goal in regional taxation is reflected in the fact that there is no provision for any form of tax benefits for investing in technologies that create less pollution and in the fact that there is no tax on CO_2 emissions, although other emissions (SO_X or NO_X) are taxed. Furthermore, as may be seen in the chart below, the taxes created have essentially penalised emission-free (nuclear) and low-pollution power plants (hydroelectric, wind), while favouring the types of generation plants that create more pollution (coal, gas, gas–oil) (Fig. 4).

There has been an alarming absence of coordination between the central government and the Autonomous Regions, which has created contradictory messages in the various legislations. On the one hand, the existence of different taxes in different regions has led to a break in the single market and the transfer of revenue between Autonomous Regions. Rather than environmental logic, the logic of revenue has been applied, meaning that the regions have ended up applying taxes to installations that already existed in their territories, regardless of their environmental impact, instead of preventing the creation of others that might create more pollution.

At national level, one recent example of legislation that was initially proposed on environmental grounds but ended up as a purely revenue-oriented instrument is Act 15/2012 of 27 December on fiscal measures for energy sustainability. This Act mostly consists of new charges and fees applied to the activities and assets of the Spanish electricity sector.

Lastly, it should be noted that this analysis does not look at the impact of other, non-fiscal regulations, which also have a certain effect on the environmental signal transmitted via energy prices. In contrast with more balanced plans, such as the

European Commission's recent 20–20–20 targets, the government has often mixed up the concepts of regulation and taxation, overlooking the indispensable complementarity between the two, and thus creating an uncoordinated system as far as environmental and energy legislation is concerned. Therefore, the current tax structure is not effective in addressing the challenges faced by the Spanish energy model, which requires strong incentives in favour of those technologies which are most efficient and have least environmental impact, and a stable framework to regulate activity regardless of regional preferences, so as to avoid pseudo-environmental taxation. Moreover, *ad valorem* taxes and subsidies on fossil fuels, or on the list of prices applicable to the various energy products, fail to comply with the optimal fiscal design principles set out at the beginning of this chapter as they do not reflect the actual damage produced by each energy source. The main challenge faced by regulators in Spain as regards matters of taxation is thus precisely how to establish a taxation framework that is capable of guaranteeing the long-term sustainability (in the broadest sense of the word) of our system.

4 Supporting Frameworks for Renewable Energies

4.1 Existing Supporting Frameworks for Renewable Energies

Directive [9] 2001/77/EC on Renewable Energies marked one of the first milestones in the promotion of renewable energies in the EU. The Directive was based on the 1997 White Paper on Renewable Energy Sources, which set a target of having renewable energies account for 12 % of the gross energy consumption in EU-15 by 2010 and the electricity generated from those renewable sources account for 22.1 %. The 2001 Directive gave the Member States total freedom to establish their own supporting frameworks. Therefore, the EU has basically committed to a combination of an indirect method—, the EU ETS, which penalises generation facilities that produce CO_2 emissions compared to those that do not—with direct methods at national level. Direct methods are dependent on the fact that the indirect method is insufficient to guarantee the competitiveness of using renewable rather than conventional energies. There are various different types of direct method.

These supporting systems can function by regulating the sale price of the electricity generated from renewable sources, either by introducing a fiscal or financial benefit per kW of installed capacity, or by deciding in full or in part what tariffs must be paid for each kWh generated and uploaded to the grid from a renewable source. In both cases, the market is accountable for the result in terms of the capacity to be installed. In other cases, the supporting framework is based on establishing a target power or generation level to be reached, in absolute or relative terms, and letting the market decide the price payable to generators for the renewable energy produced (Table 1).

Table 1 Direct methods for supporting renewable energies

	Regulated price	Regulated quantities
Based on investment	Investment subsidies Tax credits	Auctions
Based on production	Tariff/Premiums	Quota system and green certificates

According to the information gathered by the Council of European Energy Regulators (CEER) for its report of June 2013,[16] the majority system in the European Union is based on feed-in tariffs or feed-in premiums. Under this supporting framework, generators of electricity from renewable sources are entitled to sell all of their output. They do so at prices that are either fully decided (total regulated tariff) or only partially decided by law (regulated premium or incentive added to the price per kWh in the electricity market).

Another supporting framework that widely used in Europe is the quota and green certificates system, which has been running with variations in some EU countries for several years (e.g. Italy, Belgium, UK). It is essentially based on legally obliging electricity consumers, suppliers or generators, depending on the case, to obtain a particular percentage or quota (which generally increases over time) of their electricity supply or output from renewable energy sources. At the end of each consecutive period under consideration (usually a year), the parties bound by the quota must prove their compliance by submitting to the relevant National Regulatory Authority a number of green certificates equivalent to the quota specified. One green certificate is usually equivalent to one MWh of renewable energy.

Lastly, another supporting system that has been implemented to a certain degree, notably in France and Portugal, is based on an auction system. In this case, developers are invited to submit bids for a limited quantity of power or energy in a given period. The companies that offer the supply at the lowest cost are awarded long-term contracts, generally for a period of between 15 and 20 years.

The 2001 Directive was amended and replaced by the Renewable Energies Directive [6] 2009/28/EC, which has been consolidated as the basic regulatory framework for promoting renewable energies in Europe. It sets compulsory national targets that are consistent with achieving the European target of having renewable account for 20 % of final energy consumption in the EU by the year 2020 and 10 % in the case of the transport sector. This Directive has introduced elements designed to simplify the administrative regimes applicable to renewable and regulatory improvements that facilitate access by electricity systems to electricity generated from such sources. It also provides for an overall sustainability system for biofuels and bioliquids, with obligations as regards monitoring and information.

Apart from these basic elements, the Renewables Directive, as it is known, maintains countries' freedom to define their own supporting frameworks.

[16] CEER [3] "Status Review of Renewable and Energy Efficiency Support Schemes in Europe". 25 June 2013.

The following table summarises the main supporting frameworks in place, listed by country and by the type of technology involved (Table 2).

In what follows the main results of these supporting frameworks are analysed from an empirical perspective and in terms of their effectiveness and efficiency, using the progress reports issued by the European Commission (Renewable Energy Progress Report COM [27], p. 175) and the Status Review of Renewable and Energy Efficiency Support Schemes in Europe of 25 June 2013, published by the CEER. This information serves as the basis for the conclusions drawn and for justifying the proposals made in Sect. 2.2.

The report drawn up by the European Commission starts by analysing the extent to which the targets that marked out the course of the Directive for the years 2012/2012 were reached. It then goes on to analyse the prospects for future growth in terms of meeting the target for 2020. In this latter case, it looks at the gap between what was planned for each technology (targets) and the estimated future roll-out, in terms of the current regulatory and economic conditions.

As regards diagnosing the extent to which targets are now being met, the Commission seems optimistic. As a result of the implementation of the Renewables Directive and the national measures defined in the plans of action on renewable energy, most Member States have witnessed significant growth in renewable energy since the previous report on the matter was drafted by the Commission.[17] In fact, the quota for renewable energies in twenty Member States and in the EU as a whole in 2010 was the same as or higher than the commitments for that year stated in their national plans and higher than the first intermediate target for 2011/2012.[18] As can be seen in the following bar chart, most of this success is due to the high degree of implementation of renewables in the electricity sector. In the transport sector, 22 Member States failed to attain their indicative target of 5.75 % for 2010 (Fig. 5).

Looking ahead, the Commission appears to be less optimistic. The economic crisis, the current obstacles in terms of administrative issues and infrastructure and changes in policies and supporting frameworks all suggest that a fall-off in future investments is highly likely, compared to the levels of investment planned in the renewable energy plans of the Member States. Nonetheless, there are differences in this trend depending on the technology. While wind power (onshore and offshore), biomass and biofuels predictably fail to attain the levels planned for them, solar photovoltaic is set to exceed its planned level as a result of disproportionate growth due to a supporting framework that has offered incentives not linked to changes in costs for this technology.

In the case of wind power, the European Commission report points out that according to the Member State plans, wind power capacity should reach 213 GW in 2020 (169 GW on land and 44 GW offshore). This capacity would lead to wind

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[17] Renewable Energy: Progressing towards the 2020 Target (COM (2011), p. 31 and SEC(2011), p. 130).

[18] The interim targets are included in the indicative trajectory provided in Annex I, Part B, of Directive [6] 2009/28/EC. The interim target for the EU for 2011/2012 was 10.7 %.

Table 2 Types of supporting frameworks in Europe, arranged according to technology (2012) *Source*CEER (2013) Status review of renewable and energy efficiency support schemes in Europe

	Hydro	Wind	Biomass and waste	Biogas	Photo-voltaic	Geo-thermal
Austria	Investment grants, Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	Investment grants, Feed-in tariff	Feed-in tariff
Belgium	Green certificates with guaranteed minimum price	Green certificates with guaranteed minimum price	Green certificates with guaranteed minimum price	Green certificates with guaranteed minimum price	Green certificates with guaranteed minimum price	Green certificates with guaranteed minimum price
Czech Republic	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium
Estonia	Feed-in premium	Feed-in premium	Feed-in premium	Feed-in premium		
Finland	Excise tax return	Excise tax return	Excise tax return	Excise tax return		
France	Feed-in tariff	Feed-in tariff Call for tenders	Feed-in tariff Call for tenders	Feed-in tariff	Feed-in tariff Call for tenders	Feed-in tariff
Germany	Feed-in tariff, Direct marketing Feed-in premium	Feed-in tariff, Direct marketing Feed-in premium	Feed-in tariff, Direct marketing Feed-in premium		Feed-in tariff, Direct marketing Feed-in premium	Feed-in tariff, Direct marketing Feed-in premium
Hungary	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff
Italy	Green certificates Feed-in tariff	Green certificates Feed-in tariff	Green certificates Feed-in tariff	Green certificates Feed-in tariff	Feed-in premium	Green certificates Feed-in tariff
Lithuania	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	
Luxembourg	Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium		Feed-in tariff Feed-in premium	Feed-in tariff Feed-in premium	
Netherlands	Feed-in premium	Feed-in premium	Feed-in premium		Feed-in premium	
Norway		Investment grants				

(continued)

Table 2 (continued)

	Hydro	Wind	Biomass and waste	Biogas	Photo-voltaic	Geo-thermal
Portugal	Feed-in tariff	Feed-in tariff Tendering process	Feed-in tariff Tendering process	Feed-in tariff	Feed-in tariff	
Romania	Green certificates	Green certificates	Green certificates	Green certificates	Green certificates	
Slovenia	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	Feed-in tariff	
Spain	Feed-in tariff or Feed-in Premium (optional)	Feed-in tariff or Feed-in Premium (optional)	Feed-in tariff or Feed-in Premium (optional)	Feed-in tariff or Feed-in Premium (optional)	Feed-in tariff (PV) and Feed-in tariff or Feed-in Premium (CSP)	***
UK	Green certificates Feed-in tariff	Green certificates Feed-in tariff	Green certificates		Green certificates Feed-in tariff	

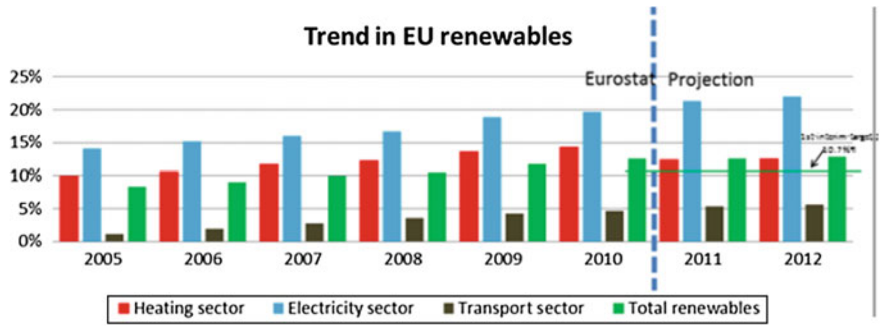


Fig. 5 Sectoral and overall growth of renewable energies in the EU (Eurostat) *Source* Renewable Energy Progress Report COM [27], p. 175 final. 27 March 2013

power generation amounting to almost 500 TWh in 2020. However, estimates based on current trends indicate that there is a risk that wind power may only reach around half the capacity planned, at 253 TWh.

For biomass in general the trend is also negative, although less so than in the case of wind power.

As regards solar photovoltaic energy, the situation and the expectations are very different, as the scheduled targets have been exceeded at practically every stage in the period. The strong growth in recent years has created a surplus that will continue for quite some time. The EU's verdict in the report is very clear: "An optimistic and secure EU market helped lead to a build-up of global PV production capacity, as China, India and the US entered into a new, EU-triggered global PV market. The resulting overcapacity has brought production costs down significantly. However rigid national support schemes were generally unable to adapt rapidly enough to such falling costs, raising profits and creating a rate and scale of installations in some countries almost excessive in a time of general economic crisis (Figs. 6, 7)."[19]

As stated previously, to gain an understanding of the differences in the stages of implementation of the various renewable technologies it is useful to analyse the levels of support received by each one. The table below (taken from the CEER report) shows how solar photovoltaic energy has received levels of support far in excess of other technologies. Moreover, bearing in mind that in most cases that support has been provided in tariffs that guarantee the tariff for the installation over very lengthy periods, it is easy to understand why there has been a disproportionate response (or "bubble") surrounding the roll-out of this technology in countries such as Spain, Italy and Germany (Table 3).

An analysis of the supporting frameworks for renewable energies leads to very interesting conclusions on the basis of experience in Europe, with various success stories and failed initiatives.

[19] COM (2013), p. 175 final.

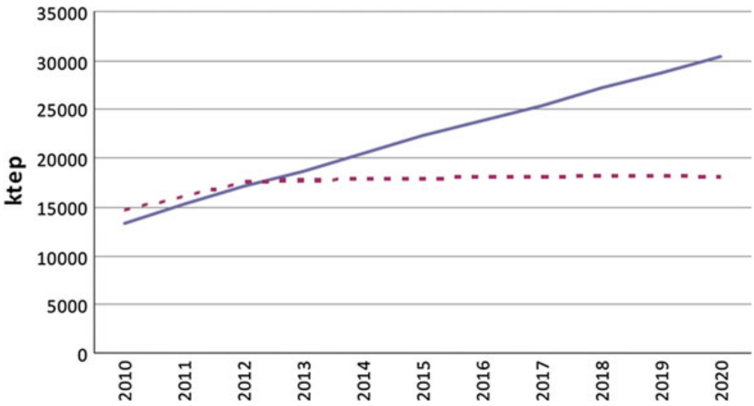


Fig. 6 Planned (*blue*) versus estimated (*red/dotted*) trend in EU onshore wind power

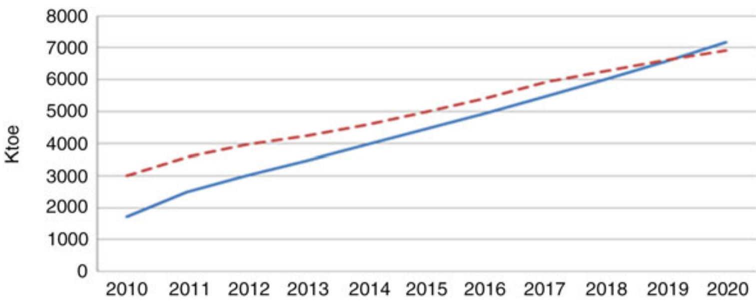


Fig. 7 Planned (*blue*) versus estimated (*red/dotted*) trend in EU solar photovoltaic energy Source Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Renewable Energy Progress Report. COM [27], p. 175 final. Brussels, 27 03 2013

In general terms, experience shows that systems which work for one type of technology do not necessarily work for others based on very different cost levels or levels of technological development. Empirical evidence also reveals that supporting frameworks have in general been effective in promoting the roll-out of renewable energies in Europe. However, enough priority has not been given to efficiency, which is set to become an increasingly important issue as the share of renewable energies in the energy mix grows.

Premium systems in particular may be considered to have been effective in the light of the expanding roll-out of renewable energies in European electricity systems. However, from the point of view of efficiency, there have been major drawbacks. One very significant consequence of the disproportionate development of some renewable technologies is the increasing need for support, which is funded in most systems by electricity consumers (via the revenue collected from electricity tariffs). This has increased the cost of the electricity supply even more in those

Table 3 Weighted average support level (on electricity supported) by technology (€/MWh)

	Hydro	Wind	Biomass	Biomass And waste	Photo-voltaic	Geo-thermal	Total
Austria	1.13	21.55	81.12	98.20	263.64		46.49
Belgium	45.17	94.58	96.57		407.42		142.04
Czech Republic	57.08	63.56	55.06	107.50	432.33		196.32
Estonia	51.61	53.68	53.68	56.25			53.66
Finland	4.20	11.97	6.74	4.20			6.93
France	13.17	33.04	54.85	41.45	477.22		116.00
Germany	48.66	45.43	143.74	25.97	353.82	157.59	130.77
Hungary	71.78	111.48	112.97	108.77			107.33
Italy	70.30	69.00	119.90		367.20	80.00	153.69
Luxembourg	79.33	36.38		70.46	543.43		138.21
Netherlands	103.93	68.47	75.11	41.33	385.88		70.89
Norway		11.27					11.27
Portugal	40.54	42.68	49.16	39.51	291.78		47.03
Romania	59.81	65.17	63.77		78.74		64.39
Slovenia	23.47	95.38	87.24	126.76	343.07		81.05
Spain	39.02	40.94	75.11	31.26	356.76		84.80
Sweden							21.47
UK	64.81	72.71	58.48	62.80	290.37		59.92
Minimum support	1.13	11.27	6.74	4.20	78.74	80.00	6.93
Maximum support	103.93	111.48	143.74	126.76	543.43	157.59	196.32

Source Status review of renewable and energy efficiency support schemes in Europe *Ref* C12-SDE-33-03. 3 December 2012 . Revised: 19 February 2013

countries where the bubble is largest. The following graph illustrates the extent of the support paid for by electricity consumers in each country for each MWh of electricity consumed in relation to the share attained by renewables. It is noteworthy that Spanish and Portuguese consumers lead the cost ranking (Fig. 8).

In theory auction systems (or tendering processes) provide advantages (they generate competition between developers that maximises efficiency, enables the amount of installed capacity that corresponds to renewable to be monitored, offers stable returns, etc.). However, not enough have been conducted for it to be possible to compare all of these advantages properly.

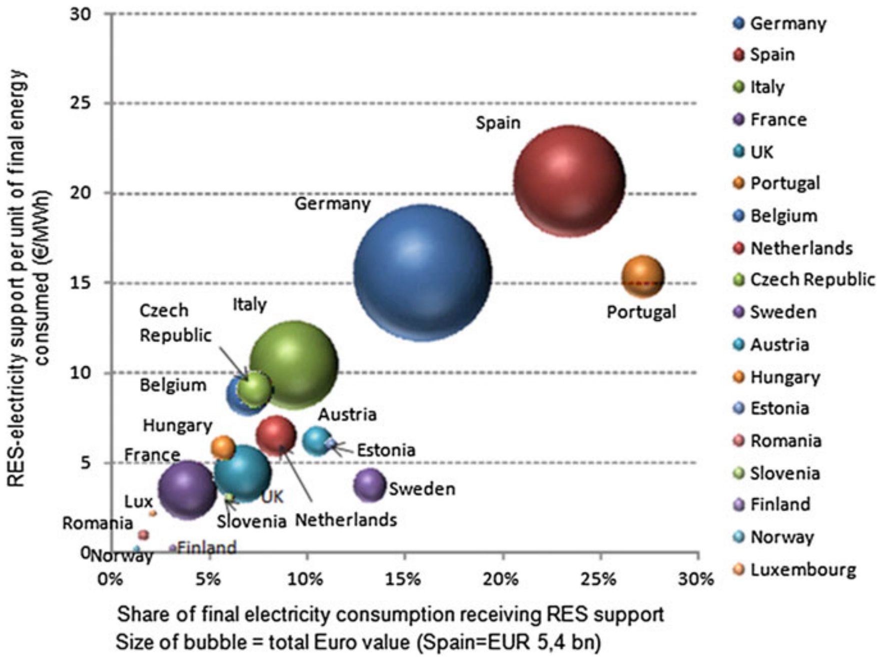


Fig. 8 Costs derived from support for renewable energy per unit of electricity consumed versus share in final energy consumption *Source* Status Review of Renewable and Energy Efficiency Support Schemes in Europe. Ref: C12-SDE-33-03. 3 December 2012. Revised: 19 February 2013

The analysis carried out in this section points to two main basic conclusions. As regards the premium and tariff systems, experience shows that although they have proved effective in attaining the targets set there is no control over the quantities being installed, and therefore in the case of technologies that evolve quickly bubbles may develop when levels of support are decoupled from costs. On the other hand, the fact that it is electricity consumers who for the most part finance support for renewable energy means that the increase in the roll-out of these technologies has a major impact on electricity bills and hence on the cost of electricity, making it relatively less competitive compared to other types of energy (natural gas, fuel-oils, etc.).

Box 2. Lack of control in the installation of solar technologies: the case of Spain

In Spain the generous tariffs and premiums assured by RD (Royal Decree) 661/2007 for solar technologies encouraged disproportionate growth in the installation of solar photovoltaic and solar thermoelectric technologies, meaning that the targets set in the Renewable Energies Plan (and RD 661/2007) for 2010 were significantly exceeded (Figs. 9, 10 and 11).

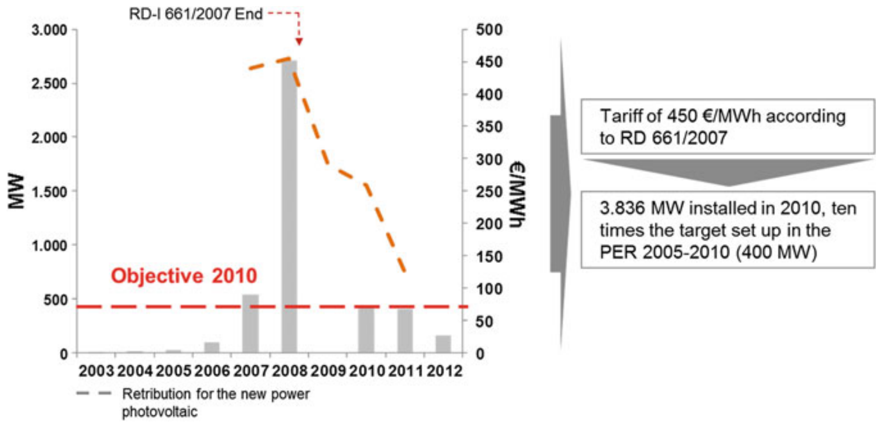
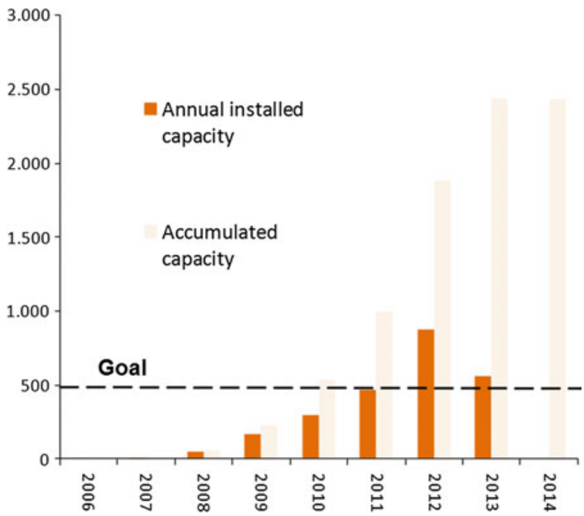


Fig. 9 Trend in installed solar photovoltaic capacity (MW). Remuneration PV type II (€/MWh) *Source* CNE

Fig. 10 Trend in installed concentrated solar capacity (MW) Source: CNE



4.2 Proposals

In the medium (2020) and long term (2030/2050), the challenge is to meet renewable energy targets in an efficient manner. In this regard, it is important to remember that many technologies are becoming increasingly competitive and it is to be expected that many of those that are not there yet will become competitive within a few years. This means that it will be necessary on the one hand to decide what kind of targets should be set, and on the other to adapt the supporting frameworks to the characteristics of each technology: premiums for those that are already mature, pilot

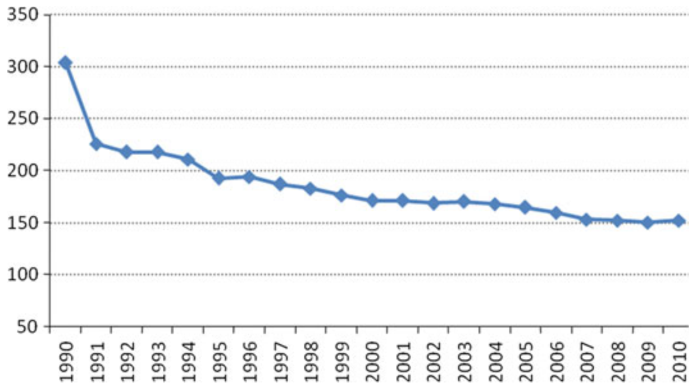


Fig. 11 Trend in energy intensity in EU 27 (ktoe/€1000) (Energy intensity of the economy—Gross inland consumption of energy divided by GDP (chain-linked volumes—reference year 2005)—kgoe (kilogram of oil equivalent) per €1000) Source Eurostat

projects for those that are immature. From the point of view of targets, experience with the 2020 goal confirms that setting various different targets has led to interference between them and, in turn, to inefficiencies. The European Commission's Green Paper asked stakeholders about this issue with a view to designing the framework for targets beyond 2020. Many of the stakeholders that responded to this public consultation revealed that they were in favour of setting a single target for reducing CO_2 emissions, so as to transmit a clear signal to encourage investments in zero-emissions technology, among which renewable energy will play a very significant role. This CO_2 target could be accompanied by indicative targets for renewables and by support for R&D&I in less mature technologies.

Bearing in mind the experience gained from the various policies to support renewable energies that have been implemented in Europe, some recommendations can be made with a view to improving the environmental and economic soundness of these policies and their compatibility with the competitiveness of the electricity supply. The main proposals can be summed up as follows:

- In order to set targets, it is necessary to perform a thorough analysis of current and future demand, in accordance with the elements that characterise the current and future context. The economic situation means that there is a need for a realistic outlook so as not to set overambitious targets when public support is required.
- A suitable role needs to be allocated to each renewable technology. The most cost-effective will be of key importance in meeting the targets and those with the greatest potential for cost reduction in the future will require smart support based on R&D or industrial policies funded by the general state budget. It is also crucial to analyse the potential for and cost of development in all energy sectors—heat and cold, electricity and transport—as they are all responsible for meeting the target of 20 %.

- Supporting frameworks should be adapted to the characteristics of each technology. Providing incentives for mature, stable technologies is not the same as providing them for energies which may be more expensive but which have great potential for cost reduction.
- As regards the allocation of cost overruns incurred in renewable development, although it is efficient to concentrate more renewable development in the electricity sector because it is the most cost-effective, it does not make sense to expect electricity consumers to bear the full cost. Therefore, the cost of renewables should be allocated to consumers of all final types of energy (heating, electricity, gas and oil), as it is they who generate the need for development.
- The timeline for roll-out should be adjusted in order to minimise the cost of compliance with the Renewable Energies Plan. It is important to adapt the development of renewables to meeting targets in 2020 and not before, so that it is possible to develop a spin-off industrial sector that is sustainable over time.

As well as the foregoing, if renewables are to penetrate the electricity sector efficiently it is vital to acknowledge the support/back-up provided by firm, flexible conventional technologies (particularly hydro power plants and natural gas combined cycles). It is also essential to boost the levels of interconnection in Europe from the current situation. A penetration rate of some 40 % by renewables in 2020 might in some cases mean very high coverage for electricity demand: higher than is currently the case. Obviously this would generate significant risk because the demand could not be guaranteed with non-firm energies such as those referred to as "intermittent" renewables (wind and solar power). There is also the issue that there needs to be sufficient capacity to deal with fluctuations in demand and fluctuations as a result of those technologies that cannot be controlled.

5 Regulations to Promote Energy Efficiency

5.1 A General Approach to the Regulation of Energy Efficiency in the EU

The European Union is among the economic areas that have spearheaded improvements in energy efficiency. This is due to the following factors: on the one hand the major structural changes in the economy of this group of countries (in general terms, the economy has been outsourced, and the most energy-intensive industries have been relocated to other economic areas), and on the other the implementation of various different policies and regulatory instruments designed to improve energy efficiency (Figs.11, 12).[20]

[20] This section is based on Muñoz Rodríguez et al. [22] WP 12/2013. "Reflexiones sobre los esquemas de obligaciones de ahorro energético (certificados blancos) en Europa". *Economics for Energy*.

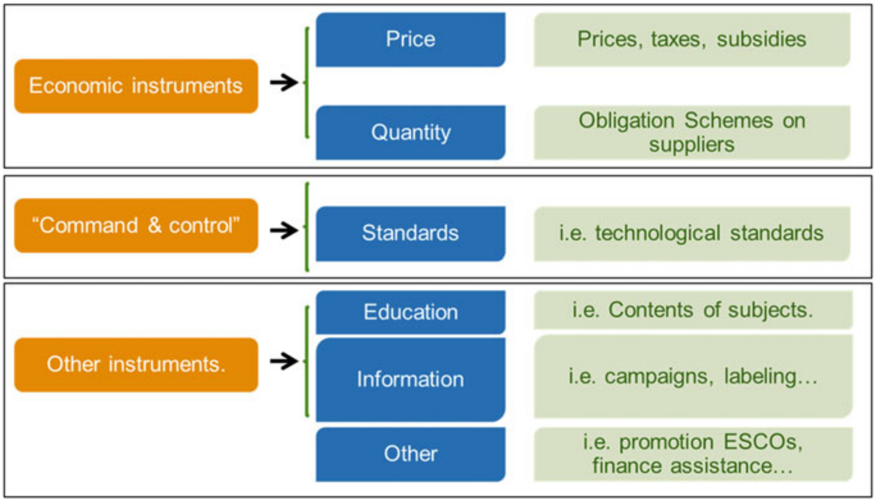


Fig. 12 Main regulatory instruments for improving energy efficiency *Source* own records

In fact a large proportion of the improvements achieved in energy efficiency are due to the application of policies and regulatory instruments to overcome barriers and correct the market failures that prevent investments in efficiency from attaining optimum levels. The huge variety of regulatory instruments that have been developed in the European context can be grouped into four main areas: economic instruments affecting price and quantity, “command-and-control” measures, measures designed to enhance information, awareness and the possibilities available to consumers, and “other measures”.

Economic measures based on the introduction of price signals are implemented by governments in order to attain an energy efficiency target, under the assumption that the price signal will have a major impact on consumption. Highlights of these measures include prices that reflect the costs of energy and external issues, energy and environmental taxation and redefining the tariff structure.

The second group of economic instruments involve setting efficiency targets. This makes them quantity-based economic instruments in which governments impose targets on distributors and/or energy suppliers to get them to bring down their customers’ consumption within a certain period. In general, the companies themselves can decide what procedures to carry out in order to meet these obligations. This type of instrument is used in various EU countries (UK, France, Italy, etc.) and was granted a special role in the recently passed Energy Efficiency Directive. A more detailed analysis of these instruments is therefore presented in this section.

One instrument is described in the literature in the section on “command-and-control”: it consists of setting minimum compulsory norms and standards for consumer equipment (vehicles, buildings, electrical appliances and other electronic devices). This is usually considered to be a highly suitable measure for achieving structural improvements in energy efficiency and it has been rolled out to a high degree throughout Europe. In many cases, these standards have been set on a centralised basis for the EU as a whole.

There are also measures designed to enhance information, heighten awareness and improve the possibilities available to consumers. These measures include information campaigns, energy labelling for equipment, energy audits and the funding of investments in energy efficiency (mostly reductions in taxation, though there are also subsidies). There are also special benefits for low-income families, e.g. in the United Kingdom. Despite the importance of achieving a high degree of awareness in society regarding energy efficiency and of improving the possibilities available to consumers when making decisions on consumption and investment with a view to reducing their energy consumption, the efficiency of this type of measures is diminished if energy prices fail to incorporate all the costs of supply or if consumers are unable to estimate all the costs associated with their energy consumption.

The group referred to as "other measures" comprises provisions of various kinds that are instrumented in all of the countries examined. Chief among them are the adoption of standards for the construction and refurbishment of buildings, the promotion of energy service companies (ESCOs), stricter regulations for the public sector as regards building and supplier approval, voluntary agreements with companies and funding for R&D. In general, it is hard to predict how effective this type of provisions will be, and they depend on the existence of a regulatory framework containing the right economic instruments to encourage investments in efficiency.

The European debate on the suitability of the various policies or regulatory instruments for helping to improve energy efficiency was further boosted with the passing in October 2012 of the Energy Efficiency Directive, which is now in the process of being transposed into law in the various Member States, and which includes or builds on most of the instruments analysed in this section.

5.2 The Energy Efficiency Directive

The Energy Efficiency Directive [7] 2012/27/EU (EED) proposes overall as well as sectoral targets, regulatory instruments, measures to promote funding for efficiency measures and a conceptual framework for monitoring and supervising the progress made in this regard.

In relation to targets, the overall goal at European level is to achieve a 20 % reduction in primary energy consumption in the EU by 2020 compared to the projection for the year made in 2007. This means that primary energy consumption in the EU should not exceed 1,474 Mtoe (1,078 Mtoe in terms of final energy consumption) in 2020.

On the basis of this overall target set for the EU, the Directive provides that each Member State should set an indicative target for energy efficiency based on energy consumption (primary or final) or on energy intensity.

The regulatory instrument with the greatest impact is described in Article 7, which details an energy efficiency obligation scheme with targets for the Member

States and regulatory alternatives for achieving them. These obligations on suppliers or distributors (commonly referred to as “white certificates”) have sparked the most debate, as a result of different positions regarding their characteristics and impact in terms of cost and results.

Box 3. Reflections on energy efficiency obligation schemes (white certificates) in Europe

An energy efficiency obligation system or “white certificate system” (when trading with certified savings is allowed) is a regulatory instrument that obliges the parties in question (generally energy companies) to achieve a certain degree of energy savings both in their own sector and elsewhere (other industrial sectors, the residential or commercial sector, etc.). These savings may be made by implementing various measures, which must be approved or acknowledged in some way by the competent authority. Such systems therefore require a way of verifying and measuring the effective implementation of measures leading to the specified savings.

The profile of “white certificate” systems has risen as they have spread to more countries. Frameworks of this kind are currently in place in Italy, France, Denmark and the United Kingdom, and in the Belgian region of Flanders. There are also plans for their implementation in Ireland and Poland. There are still many unanswered questions as regards their effectiveness and efficiency, given the limited experience in their application, the lack of transparency and the difficulties encountered in comparing relatively complex frameworks in very different commercial settings. These issues are developed in greater detail in the section on analysis.

One important element to be taken into consideration when analysing white certificate schemes is that they focus on the behaviour of the energy supplier (or distributor) but not on that of the consumer. In this regard, investments made by consumers (for example, improvements in insulation) do not necessary have an impact on their awareness or behaviour as regards energy savings. In fact, reducing the effective cost of energy (if efficiency is increased after the measures) could lead to a “rebound effect” to some extent. How big that “rebound effect” might be is still the object of considerable debate. However, there is a degree of consensus that it is unlikely to be big enough to mitigate the effect of the measure. The study by Greening, Greene and Defiglio [16], which reviews prior literature on the “rebound effect” and energy efficiency, does not overlook these problems but concludes that the effect is in any case lower than one unit (i.e. it does not exceed the savings achieved), meaning that energy efficiency is still a tool that can achieve positive results. Moreover, analysis of the existing frameworks has failed to provide conclusive evidence that white certificate systems promote the implementation of the most cost-effective and most efficient measures, or even that they meet the requirement of “additionality”. This is partly because of the duration and characteristics of the obligation periods and partly because of the type of measures that are liable to receive certificates. Rather, it seems that it is the easiest measures or the ones for which certificates are most likely to be received that are usually carried out, and that these are not necessarily the most efficient ones. When the obligation period is short, the tendency is likely to be to choose cheaper, more short-term measures rather than measures that would require greater initial investment but save more energy in the long term. Moreover, in some cases (for example, in France and Italy), some measures receive double support (both tax credits and certificates), which also raises doubts as to the efficiency of the system as a whole. In this regard, there are still unresolved doubts regarding the structural savings that can actually be achieved by these frameworks, as the data available are not clear or comparable enough to ascertain the actual volume of savings achieved.

5.2.1 Obligations on Energy Suppliers

Article 7 of the EED imposes on Member States the obligation to develop a system of energy efficiency obligations for energy suppliers, setting an annual savings target (for the period 2014–2020) equivalent to 1.5 % of the annual energy sales of all their retail energy distributors or suppliers, in volume, as the average for the three years before 1 January 2013. Some issues regarding this target are the following:

- The parties obliged to meet this target may be distributors, suppliers or both.
- There is no specification as to what energy sectors are to be subject to this system. For example, energy consumed in transport might not be included.
- From the point of view of additionality, the Directive implies that every Member State will be obliged to achieve further savings every year equivalent to 1.5 % of sales in the three years prior to 1 January 2013. For example, if the average sales were 100 Mtoe, then the savings progress required in the period would be as follows (Table 4):

Article 7 in fact means the imposition of an energy savings target for the Member States, which will be given significant flexibility as to how they meet it via

Table 4 Example featuring additional annual savings required under article 7 EED

2014	1.5 Mtoe
2015	3 Mtoe
2016	4.5 Mtoe
2017	6 Mtoe
2018	7.5 Mtoe
2019	9 Mtoe
2020	10.5 Mtoe
Total	42.0 Mtoe

various mechanisms, either as part of the obligation scheme or by implementing regulatory alternatives aimed at achieving the target. Both these alternatives are specified with the possibility of replacing the obligation scheme with an alternative regulatory framework (with taxes, standards, etc.) or with a national fund for energy efficiency to which stakeholders make contributions in order to fund energy efficiency measures.

5.2.2 Flexibility in Meeting Targets (Maximum 25 %)

As discussed above, article 7 of the EED offers flexibility[21] as regards how the target is met. However, it provides a closed list of flexibility measures and limits their application to a maximum of 25 % of the energy savings that would be derived from the original target of 1.5 %. The following are the main flexibility measures:

- Flexibility in target progress: 1 % (2014 and 2015); 1.25 % (2016); 1.5 % (2018, 2019, 2020).
- Exclusion of sales to sectors subject to the EU ETS.
- Possibility of including in the calculation savings derived from measures implemented since January 2009 (with effect in 2020).
- Inclusion in the calculation of energy savings derived from co-generation, tariffs, smart metres, etc.[22]

5.2.3 Degree of Discretion in Designing the Obligation System

In principle, the European regulation offers Member States considerable scope for manoeuvre as to the supplier obligations framework, listing a number of elements, many of which are commonly used in countries where this type of frameworks are in place, but not making their inclusion compulsory.[23] These elements include:

- Banking/borrowing of savings (for 3 or 4 years).
- Introduction of an obligation for parties subject to the regulatory framework to carry out measures for households in "energy poverty" or affected by certain types of social vulnerability.
- Inclusion of the transport sector. The possibility of the energy supplied to the transport sector also being subject to these targets is left open. One important example of a framework in which liquid hydrocarbons are subject to savings obligations is the French system.

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21 "The application of the terms provided in Sect. 2 shall not lead to a reduction of over 25 % in the amount of energy savings referred to in Sect. 1". Article 3.

22 "Allow energy savings achieved in the energy transformation, distribution and transmission sectors, … to be counted towards the amount of energy savings required…".

23 See Appendix.

5.2.4 Possibility of Alternatives to the System of Obligations on Suppliers

This item in the Directive is very significant, because it grants Member States a degree of discretion as regards setting up a system of obligations on suppliers if equivalent savings are achieved through regulatory measures or energy and taxation policies such as the following:

- Taxes on energy or CO_2.
- Tax or financial incentives.
- Voluntary agreements.
- Standards and norms (not previously compulsory).
- Labelling.
- Training and awareness measures.

5.2.5 National Energy Efficiency Fund: Funding and Technical Support

As well as the alternatives listed in the previous item, there is also the possibility of creating what is referred to as a National Energy Efficiency Fund (Article 20), which allows a Member State to achieve savings equivalent to the 1.5 % target of a system of obligations on suppliers, by simply creating a fund towards which the obligated parties would then make financial contributions:

> 6. Member States may provide that obligated parties can fulfil their obligations set out in Article 7(1) by contributing annually to the Energy Efficiency National Fund an amount equal to the investments required to achieve those obligations.

In short, although the Directive defines obligations in relation to energy efficiency at supplier level for Member States, the energy efficiency obligation system may be partially or fully replaced by a regulatory framework that enables equivalent savings to be made or by a fund to which the stakeholders subject to the targets must contribute. The following diagram sums up the regulatory frameworks that could be used in order to attain the 1.5 % target (Fig. 13).

5.2.6 Role of the Public Sector

The EED considers the public sector to be one of the priority areas for savings. The proposals in this regard are based on European experience in this field, with the public sector becoming a major driver in the energy services market, because of the high significance of its investments and its purchasing power. It therefore sets as an explicit savings target for the public sector in each Member State the obligation

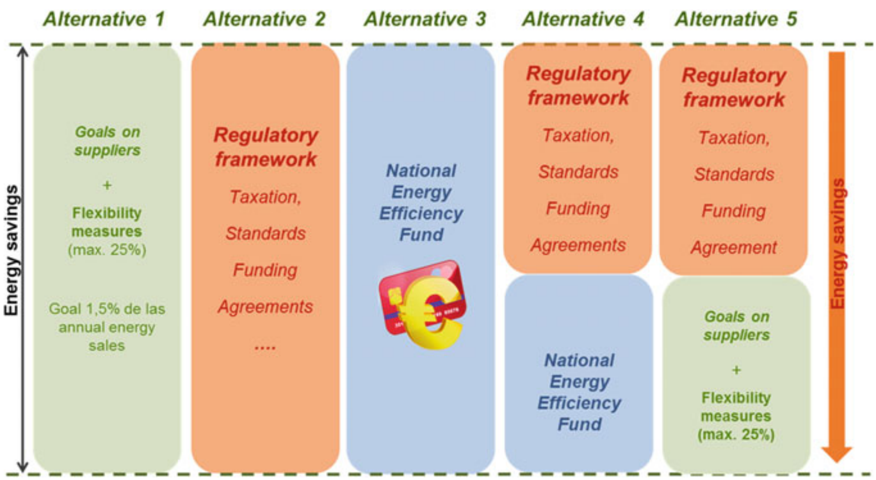

Fig. 13 Possible regulatory frameworks for energy efficiency under Article 7 of the Energy Efficiency Directive Source own records

to renovate 3 % per annum of the total floor area of buildings owned and occupied by central government in order to increase their energy efficiency:

- This obligation applies to buildings with a floor area of more than 500 m^2;
- The following are exempt from compliance with this target: buildings that have special historical merit or which are part of a designated environment; buildings serving national defence or religious purposes, etc.

As in the case of the obligations schemes on suppliers, public bodies may also meet this target by making financial contributions to an energy efficiency fund.

5.2.7 National Energy Efficiency Action Plans

By 30 April 2014, and every three years thereafter, Member States must submit National Energy Efficiency Action Plans providing details of national energy efficiency targets and measures taken to ensure that they are met.

5.2.8 Other Measures

The Directive provides a wide range of measures but their analysis lies outside the scope of this chapter. Most of them are focused on making the most of the great potential for savings in the heating sector, improving incentives for efficiency in the field of energy networks and promoting consumer information and awareness.

5.3 Analysis and Assessment of the Regulatory Framework for Energy Efficiency

The European regulatory framework, and the EED in particular, contains a broad spectrum of regulatory instruments which are commonly used to address the barriers and market failings that prevent full potential from being reached in the area of energy efficiency.

Energy prices are considered by many authors to be the most useful of all economic instruments in promoting energy savings and efficiency. In many cases, there is a need to act on them because they do not include external issues or are not high enough to encourage consumers to rationalise their consumption.[24] Some studies go beyond the use of prices to send signals that encourage energy savings and also consider the hypothesis of induced innovation, according to which an increase in energy prices leads to technological changes that enable improvements to be made in energy efficiency (Newell et al. 1999).

Price measures have the advantages of being easy to implement and of their low incremental cost for the administration, but they are unpopular because they mean an increase in the cost of supply for consumers. To reduce popular dissent, in some cases the revenue collected from these taxes is allocated to aims with an environmental or social component (measures to combat climate change, care for certain ecosystems, grants to low-income consumers, etc.). Although their impact may be limited, because there is less flexibility in the short term, international experience has proven them to be the most effective and efficient measures in attaining energy efficiency targets.

In the case of standards there is the risk of a “rebound effect”, i.e. of energy consumption increasing in certain sectors. Therefore they must be designed very carefully. On the supply side, more efficient machinery may imply greater energy consumption in the production process. On the demand side, more efficient electrical appliances may be kept on for longer (e.g. air-conditioning).

One of the main barriers traditionally been identified in the diagnosis by the European Commission and aggravated by the economic crisis is a shortage of funding due to the diminished financial capacity of public bodies, companies and households alike. The need to raise economic resources in order to make investments was probably behind the proposal for a framework of obligations on suppliers as the main regulatory instrument included in the Directive, in the light of European experience in this field. However, there are still many unanswered questions as to its effectiveness and efficiency, given how limited its application has been to date, its lack of transparency and the difficulties encountered in comparing

[24] Richmond and Kaufmann (2006) conclude that including energy prices in the analysis of energy intensity helps to explain its changes over time in many countries. Other authors Metcalf (2008) claim that enhanced energy efficiency appears to have followed improvements in the energy efficiency of processes, partly led by prices and not by structural changes.

relatively complex frameworks in very different commercial settings. Those questions include the following:

- There are significant costs associated with system administration and transactions (which may be avoided with other schemes). The transaction costs in the British system are estimated to account for 18 % of the total. In the case of Denmark, the transaction costs payable by obligated distributors represent about 15 % of the total. However, the lack of transparency as regards implementation and administration costs is noteworthy.
- In general, they are not designed to implement those measures which are most cost-effective, most efficient, or even those that meet the "additionality" requirement, but rather only those that provide the most credit or the most certificates. This is a critique that has been made regarding all the schemes of this type set up in Europe, and it was the main reason behind the recent review of the British scheme.
- They are associated with a high degree of regulatory intervention. In fact, all the systems set up in Europe have been the object of frequent reviews during their validity period, with the consequent regulatory risk for investors.
- In many cases the gains in efficiency derived from the trading of savings are not leveraged. One of the virtues usually associated with obligations of this kind is the possibility that they may be traded in order to reduce the cost of compliance. However, international experience indicates that only in Italy have the possibilities for exchange been properly leveraged (elsewhere stakeholders have shown an inward-looking self-supply strategy).
- There are doubts as to the structural results that can be obtained from these frameworks and as to a possible rebound effect. The frameworks do not act on consumer behaviour (only on that of the energy supplier or distributor), which means that if energy becomes cheaper as a result of savings measures higher energy consumption may result.
- A very significant portion of the potential for savings cannot be realised. The fact that the transport sector is excluded from most such frameworks means that opportunities for savings are wasted in a sector that often accounts for around 40 % of energy consumption.
- The structure of these frameworks may have a negative effect on equity. In general, consumers affected by energy poverty have no possibility of saving, so although the costs of implementing the measures are paid out of the tariffs charged to all consumers, only those that have the possibility of reducing their consumption can benefit from them.

5.4 Proposals

No energy efficiency policy can work if the price signals received by consumers are distorted. This is the conclusion reached in most studies that analyse energy efficiency measures.[25] Therefore, before setting up a scheme of obligations on suppliers, it is necessary to analyse the regulatory framework for energy efficiency as a whole and determine whether the prices of the various energy products reflect the production costs in each particular time period,[26] including any negative external issues that they may cause.

In order to reinforce the price signal for the various energy products and include the necessary external issues, it is necessary to carry out a reform of environmental taxation as follows:

- A reform in which rates are set according to the environmental damage generated by each energy source, thus allowing the costs generated by the energy consumption to be internalised in the price signal. This will help to make many energy efficiency measures more profitable.
- A reform that takes the role being played by each energy sector in funding energy and environmental policies into account, focussing accordingly on the transport sector (which accounts for 40 % of final energy consumption) so that its economic contribution towards the funding of policies in this field is increased (e.g. renewable energies).

A well-designed framework for environmental taxation would achieve the following aims: on the one hand, it would be a useful tool in achieving structural improvements in energy efficiency with a positive impact on competitiveness, and on the other it would set up a solid revenue basis with the possibility of raising resources to fund policies geared towards ensuring the economic and environmental sustainability of the energy model.

Together with a suitable framework for taxation, empirical evidence gathered in countries that have achieved significant improvements in energy efficiency points towards the appropriateness of using a combination of additional measures progress towards energy efficiency is hindered not by price but by problems linked to information. This could be the case of the residential sector, where labelling, standards, information and awareness campaigns, are widely used measures which have proven in the past to be effective in achieving savings.

Among the alternatives to a framework of obligations on suppliers or distributors, the promotion of co-generation (which could receive resources from funds obtained from CO_2 auctions) also plays a significant role. In this field, care should be taken to ensure the efficiency of investments and that costs are allocated to those that benefit from the savings.

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[25] See, for example, World Energy Council (2010): *Energy Efficiency: A Recipe for Success*, and World Energy Council (2008): *Energy Efficiency Policies around the World: Review and Evaluation*.

[26] In other words, it is not just that the price of energy products should cover all costs incurred, including environmental costs, but also that the price system needs to be sufficiently advanced to allow for price signals that can be differentiated in time, taking into account the situation of the market.

6 Conclusions

For over 20 years, the EU has taken on a clear role of international leadership in energy and environmental policy, with a strong commitment to bringing down CO_2 emissions, promoting renewables and enhancing energy efficiency. Regulatory experience has been very varied, and several kinds of regulatory, taxation and command-and-control instruments, etc. have been implemented. The analysis performed here shows that there have been hits and misses but that, in general, priority has been given to meeting targets rather than to economic efficiency considerations.

This situation was initially sustainable because it coincided with a period of strong economic growth. However, the scenario has changed radically: the economic crisis has drawn attention to Europe's difficulty in maintaining inefficient environmental and energy policies, which affect the competitiveness of industry and the welfare of society, in a context in which other economic blocs have either failed to set those same targets or managed to attain them in a more cost-effective manner.

In this new scenario, if the EU wishes to uphold its commitment to environmentally sustainable energy development it needs to find ways to reach targets more efficiently, without jeopardising the competitiveness of its economy.

One of the fundamental issues is whether one or more targets is required. In the European debate on the framework of targets and policies for the long term, we would support the setting of a single target for reducing emissions, so as to send the necessary signals for investments to be made in energy efficiency and renewable energies. This target could be supplemented by indicative targets in other fields and supportive policies, such as R&D&I schemes.

Another key issue is energy taxation: our conclusion is that this is one of the crucial elements in achieving sustainability in the energy sector. Taxation analysis should be broad in scope, taking into account the burdens that are borne by all sectors for the cost items imposed by environmental and social policies.

The benefits that renewable energies provide to society as a whole mean that their supporting frameworks should be funded from public budgets or by the energy sector as a whole. The supporting frameworks should also take into account the characteristics of each technology (particularly its competitiveness).

We believe that energy efficiency is the key vector and that it should continue to be the main commitment in the field of energy in the EU, an economic block that is highly dependent on energy and lacking in new resources. From the regulatory perspective it is a complex issue, but it is crucial to attain goals effectively and avoid the mistakes that have sometimes been made in some contexts when rolling out renewable energies.

Appendix

See Table A.1.

Table A.1 Characteristics of frameworks of obligations on energy suppliers/distributors in Europe

	Flanders region	Italy	France	Denmark	United Kingdom	
Name of scheme or programme	Rationeel Energieverbruik (Rational Use of Energy—RUE Law, in English)	Titoli d'Efficienza Energetica	Certificats d'Économie de l'Énergie	Energiselskabernes spareindsats	Green deal	ECO
Year scheme started	2003	2005	2006	2006	2013 (end of 2012)	2013
Current period	Annual targets. For 2010–2011 savings of 3.5 % (over 2,500 customers). No targets were set in 2012, as it was decided to implement compulsory measures	2013–2016	Pending launch; expected in 2013–2016	2010–2020	2012(end)–2020	2013–2015 (March)
Current target	–	Baseline year T-2 0[a]	600 TWh *cumac* (estimated; pending launch of new period)	10.3 PJ in 2010 and subsequent adjustments	Savings amounting to 4.5 million tonnes of CO_2	
Obligated parties	Only electricity distributors (16 companies in total)	Gas and electricity distributors (final consumption obligations)	Suppliers of gas, electricity, air-conditioning (cold and heat), heating oil and fuel distributors for the car sector	Distributors of electricity, natural gas, piped gas and oil traders (the latter entered the scheme voluntarily)	Gas and electricity suppliers	

(continued)

Table A.1 (continued)

	Flanders region	Italy	France	Denmark	United Kingdom	
Name of scheme or programme	Rationeel Energieverbruik (Rational Use of Energy—RUE Law, in English)	Titoli d'Efficienza Energetica	Certificats d'Économie de l'Énergie	Energiselskabernes spareindsats	Green deal	ECO
Participating institutions	Vlaams Energieagentschap (VEA)	GSE, GME, ENEA, AEEG	ADEME, DGEC, PNCEE, ATEE	Danish Energy Agency	Department of Energy and Climate Change—*Advisors, suppliers, installers and electric utilities*	Ofgem
Measures	Discretionary (mostly in residential sector)	At least 50 % in sector	Discretionary. 270 standardised measures (other proposals assessed by ADEME)	All sectors except transport, any kind of activity. May be carried out by subsidiary suppliers	45 standardised measures, mostly in residential sector.	Residential sector
Banking	Yes	Yes	Yes	No	–	–
Trading with savings	No	Yes	Allowed, but not substantial.	No	–	Yes
Penalties	€0.10/kWh	1 year to correct, economic penalty in case of recidivism	€0.02/kWh	Not defined; no cases of non-compliance reported	–	

(continued)

Table A.1 (continued)

	Flanders region	Italy	France	Denmark	United Kingdom	
Name of scheme or programme	Rationeel Energieverbruik (Rational Use of Energy—RUE Law, in English)	Titoli d'Efficienza Energetica	Certificats d'Économie de l'Énergie	Energiselskabernes spareindsats	Green deal	ECO
Costs	€60 million (figures for 2009, sum of budgets of electricity distributors)	"Unit tariff contribution" for 2009 was €92.22/toe	Public bodies: €700,000/year; Companies (figures for period 2006–2009): M€ 210 (€c0.39/kWh).	€c5.6/kWh (incl. administrative and implementation costs)		€1.5 billion per annum (estimated cost for companies)
Cost recovery scheme	Partly subsidised by regional government and partly in the form of electricity tariffs for consumers	Possibility of suppliers transferring costs to tariffs	Electricity tariffs (since 2005; tax breaks before that, and subsidies for natural gas)	Via tariffs	Complex funding system.	Suppliers are free to internalise cost into their prices

Source Own records, drawn up on the basis of information obtained from regulators and companies

[a] The Italian targets are set on an annual basis for each company with baseline year T-2. In other words, the targets for a particular company for 2013 are set according to that company's total output in the year 2011

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Economic Foundations of Energy Investments

Luis M. Abadie

Abstract This chapter examines fundamental issues in the valuation of energy investments under uncertainty, using the real options approach (ROA) and market quotations. Certain basic stochastic processes are analyzed that can be used in line with the internal characteristics of energy commodities themselves, and a simple estimate of their parameters is drawn up with quotations from the futures markets to check the goodness of fit between the model and actual data. There is also a description of the conditioning factors that must be met if the ROA method is to be applied correctly. The chapter also offers a number of examples taken from the crude oil, refined petroleum products, 3:2:1 crack spread and carbon markets.

Keywords Energy investment · Uncertainty · Real options · Energy markets · Stochastic models · Crack spread

1 Introduction

The valuation of energy assets may be a complex task, partly because they involve multiple uncertainties, long useful lifetimes and technical characteristics which in some cases mean that valuations must take into account their optimum operating mode, due to the flexibility with which they may be managed, even though that flexibility may in some cases be reduced to a choice of producing or not producing.

Companies draw up valuations taking into account their expected yields and the risks that they assume, but not all the benefits of energy investments are felt at company level[1]: such investments may have a significant impact in terms of welfare

[1] This is not exclusive to energy investments.

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which may, among other things, result in increases in GDP, improvements in health in the case of clean technologies, labor, technological development, taxes, security of supply, etc. These welfare effects may, in some cases, justify investment promotion policies: investment in renewables is a case in point. However, private firms act in accordance with the financial characteristics of investment, including those environment- and welfare-related elements that affect their cash flows. This is the case, for example, of the cost of CO_2 emissions for firms subject to the European Union's Emission Trading Scheme (EU ETS) and of investors in renewables for which subsidies are available.

There are various frameworks currently available for promoting investment in energy assets, most of them concerned with renewables.[2] They include:

(a) An initial, transitory subsidy (one-off);
(b) A constant feed-in tariff;
(c) Market price plus a fixed premium;
(d) Market price plus a Renewables Obligation Certificates (ROC) price;
(e) Other incentive schemes, such as a subsidy on capital expenditure, a partial or total subsidy on (fixed) interest rates, public support measures that impact on credit ratings, decreasing the cost of borrowing, tax deductions on investments, reductions in the tax rate, etc.

All these measures affect the yield from investments and should therefore be taken into account in the valuation process.

The progressive deregulation of energy markets, and of the electricity market in particular, has brought about a shift from a system in which margins were more or less assured to one that is increasingly riskier and requires more complex tools to value and manage energy investments and their associated risks. Market deregulation has been accompanied by the development of more and more liquid derivatives markets, where products are quoted over increasingly longer periods. These markets (be they organized or OTC) provide ever greater scope for risk management, and can serve as supports for making valuations consistently with risks when the complete market hypothesis is reasonable.

There are numerous valuation methods, some of which include impacts on welfare. Menegaki [21] reviews the literature on the valuation/evaluation of renewable energy resources and summarizes the methods used in them. He discerns four major categories:

- Economic welfare-based methods: these include stated preferences techniques (e.g., contingent valuation, choice experiments) and revealed-preferences techniques (e.g., travel cost, hedonic pricing). Menegaki states that this valuation approach produces the most inclusive values for renewable energy because these methods also take into account its nonuse value.

[2] Investment promotion policies should be internalized.

- Financial economics-based methods: these draw on option pricing and portfolio analysis. They provide a number of tools for dealing consistently and transparently with both time and uncertainty. When irreversibility considerations come to the fore, as they do in projects involving renewables, management flexibility becomes particularly valuable, and the need for enhanced valuation methods (over and above the standard Net Present Value (NPV)) is even greater. Such methods include the ROA, which is analyzed here. Fernandes et al. [11] review the use of the real option approach in the energy sector.
- Emergy analysis: the net value of an environmental product or service to human society does not stem from market forces; rather, it is determined by all the available energy used (directly and indirectly) in the work process that generates that product or service (expressed in units of a type of energy, in most cases solar). Emergy analysis thus assesses a number of inputs that are usually neglected by conventional economic valuation, and the thermo-dynamics-based measures adopted go well beyond financial prices. See for example Buller et al. [6], and Brown and Ulgiati [5].
- Economic but non-welfare-based methods: these rely heavily on cost estimates. For example, renewable energy resources are valued indirectly through the replacement cost of nonrenewable ones. Similarly, renewables do not give rise to the same external costs as nonrenewables; therefore the (saving in) abatement cost or damage cost is used as a proxy for the implicit value of renewables. See Georgakellos [13] and Richards [23], among others. However, these methods assume a more deterministic style than those above, and ignore managerial and strategic options that may appear in the future.

Graham and Harvey [15, 16] use a survey answered by 392 CEOs to analyze the practice of corporate finance with its different ways of valuing investment projects. Their results show that the internal rate of return (IRR) and the NPV were the most widely used methods, but that 26.59 % always or almost always used Real Option Methods. The main valuation techniques used were IRR, NPV, the hurdle rate, the payback period, sensitivity analysis, the earning multiple approach, the discounted payback period and Real Option Analysis (ROA). In general, simpler methods such as the payback period tended to be more prevalent at smaller firms. The evidence confirms that Small and Medium Enterprises (SMEs) in the US manufacturing sector use payback time and investment costs as the main determining factors in deciding whether to invest in energy efficiency, as shown by Abadie et al. [2].

Uncertainty has a significant effect on investment, as do other factors such as liquidity constraints, lack of access to markets, ratings (credit risk), bureaucratic obstacles, etc. In many cases, these factors hit SMEs particularly hard.

This chapter describes the foundations of and techniques for valuation under uncertainty as applied to energy assets when there are complete markets on which risks can be managed. To that end, it includes stochastic models of the performance of energy commodities accompanied by illustrative examples.

The rest of this chapter is structured as follows: Sect. 2 examines real options, emphasizing the financial characteristics of the prices of energy commodities.

Section 3 analyzes the futures markets for energy commodities, the carbon market and the 3:2:1 crack spread. Section 4 reviews the literature on numerical valuation methods and provides a few examples. Section 5 concludes.

2 Real Options and Energy

This section describes the Real Option Approach for valuing investments in Real Energy Assets under uncertainty.

Real options is an approach to capital budgeting that can perhaps be applied to the valuation of energy investment far better than to other types of real assets, because there are markets with quotes for contracts with long maturity dates. This approach considers the options available to managers, such as choosing levels of output, abandoning the plant and increasing or reducing capacity, though usually only those options considered most significant for the analysis to be conducted are taken into account.

Real options analysis (ROA) considers a problem of optimization under uncertainty of a real asset given the available options and the technical and financial constraints that may exist.

Risk originates from uncertainty, of which there are two types: Economic and technical.

Economic uncertainty is correlated with the general movements of the economy. The oil price, the carbon price and 3:2:1 crack spread[3] volatilities are examples of economic uncertainty. Such uncertainty does not generally change when a company exercises a real option, unless there is massive investment of the same type. In any event, when futures market quotations are taken into account they are generally assumed to be made with all the available information, and also to reflect the expected future behavior of agents. Economic uncertainty is therefore considered to be exogenous to the decision-making process. Increased uncertainty leads to incentives to postpone investment (if that option is available) and a higher NPV is required for investment to take place immediately. Changes in uncertainty through volatility significantly change the expected yield required to justify immediate investment. Sometimes the option to postpone investment may not exist or may be insignificant, because the timeframe of the concession for making the investment is very short or because the investment may be made by a competitor, resulting in the firm losing the business opportunity. However, there are also highly interesting real options, such as the option of choosing whether to produce or not depending on margins, choosing the optimum production level or even choosing not to produce at all.

[3] The crack spread measures the difference between the purchase price of crude oil and the selling price of finished products. In the 3:2:1 crack spread for every three barrels of crude oil processed by the refinery two barrels of gasoline and one barrel of distillate fuel are obtained.

Technical uncertainty[4] is not correlated with the general movements of the economy, and is endogenous to the decision-making process. Examples include the amount of oil contained in an oilfield and the wind load at a particular location. This type of uncertainty can be reduced to some extent (and at some expense) by conducting studies and setting up pilot plants, but it cannot be eliminated altogether.

2.1 Stochastic Process

Some simple stochastic processes are presented below. They are analyzed in greater depth in the Appendix. They all have a differential equation with a deterministic part and a stochastic part. There is one version for the real world and another for the risk-neutral world, where the market price of risk is deduced from the drift.

These stochastic processes which model the behavior of commodities serve to value real assets when their NPV depends on one or more commodities via their prices.

2.1.1 Geometric Brownian Motion

Geometric Brownian Motion (GBM) is a continuous time stochastic process that is widely used in finance to model stock prices via two components: a deterministic trend and a random element. It is presented here as a basic model prior to the development of more complex models of energy commodity behavior.

The stochastic differential equation in the real word is:

$$\mathrm{d}S_t = \alpha S_t \mathrm{d}t + \sigma S_t \mathrm{d}W_t \tag{1}$$

where S_t is the price of the commodity at time t,α is the drift in the real world, σ is the instantaneous volatility and $\mathrm{d}W_t$ stands for the increment to a standard Wiener process.

2.1.2 Inhomogeneous Geometric Brownian Motion

The stochastic differential equation in the real word is:

$$\mathrm{d}S_t = k(S_m - S_t)\mathrm{d}t + \sigma S_t \mathrm{d}W_t \tag{2}$$

where S_t is the price of the commodity at time t, k is the reversion rate, S_m is the expected price toward which the value of the commodity tends in the long term, σ is the instantaneous volatility and $\mathrm{d}W_t$stands for the increment to a standard Wiener process.

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[4] By contrast with economic uncertainty, technical uncertainty refers to the uncertainty of technical parameters, e.g., recoverable reserves.

2.1.3 The Schwartz Model

The stochastic differential equation in the real word is:

$$\mathrm{d}S_t = k(\mu - \ln S_t)S_t\mathrm{d}t + \sigma S_t\mathrm{d}W_t \tag{3}$$

where S_t is the price of the commodity at time t, k is the reversion rate, σ is the instantaneous volatility and $\mathrm{d}W_t$ stands for the increment to a standard Wiener process.

2.1.4 The Ornstein-Uhlenbeck or O-U Process

The stochastic differential equation in the real word is:

$$\mathrm{d}S_t = k(S_m - S_t)\mathrm{d}t + \sigma\mathrm{d}W_t \tag{4}$$

where S_t denotes the price at time t. This current value tends to the S_m level in the long term at a reversion rate of k. Moreover, σ is the instantaneous volatility, and $\mathrm{d}W_t$ stands for the increment to a standard Wiener process.

2.2 Risk Premium

Let λ be the market price of risk. The Risk Premium (RP) is defined as the difference between the quotation at time t of a future with maturity T and the spot price S expected for that time T, i.e. $\mathrm{RP}(t, T) = F(t, T) - E_t(S_T)$.

2.3 Equivalent Martingale Measure or Risk-Neutral Measure

In a complete market where there are no opportunities for arbitrage there is a valuation method based on incorporating the market risk and using the new probability distribution, which is the risk-neutral measure.

Basically, this means subtracting the market price of risk from the stochastic differential equation in order to obtain the performance under the equivalent Martingale measure. Assets can then be valued by discounting them at the riskless rate. This is equivalent to discounting the expected real-world value with a rate that is the sum of the riskless rate plus a RP. However, the risk-neutral measure is much easier to use, since the parameters of the corresponding stochastic process are relatively easier to estimate.[5] It is important to stress that using risk-neutral

[5] For instance by using the enormous amount of information provided by futures markets.

valuation does not assume that investors are risk-neutral: in fact they are not. Risk-neutral valuation uses risk-neutral probabilities.

For this method to be used the market must be complete, because otherwise the risk-neutral measure is not unique. With incomplete markets, there are project-specific private risks. Contingent claims can be valued by replicating portfolios of market assets or by using risk-neutral methods when markets are complete. A replicating portfolio can still be built up when only market uncertainties exist, but if some values are not traded assets then the market is incomplete. The growing number of marketplaces and market participants is markedly conducive to the application of this method. One of the most frequent causes of market incompleteness is price jumps, as found for instance in electricity markets.

The possibility of cover enables futures prices to be used instead of expected spot prices. This means a shift from the real world with a RP to risk-neutral world with no RP simply by changing the drift of the stochastic differential equation.

When the market is not complete any of the three following options may be used:

(a) Assume that the market is complete and use the above method. In this case reliability will depend on the degree of incompleteness, but the method will not be completely correct because some market values will be missing.
(b) Assume that market participants are risk-neutral and discount at the riskless rate, using the actual probabilities. This may not be a good option.
(c) Use dynamic programming with an exogenous discount rate. In this case, the problem of determining what that discount rate should be arises. This method is used in some examples by Dixit and Pindyck [9].

There is also a fourth option, consisting of establishing a utility function to make calculations, but this method is usually only used in the academic world.

2.4 Convenience Yield

The convenience yield $\delta$is the benefit or premium associated with holding an underlying product or physical good rather than the contract or derivative product. Users of a consumption asset may obtain a benefit from physically holding the asset (as inventory) prior to T (maturity) which is not obtained from holding the futures contract. Such benefits include the ability to profit from temporary shortages, and the ability to keep a production process running.

The convenience yield is equivalent to a dividend on a share. Convenience yields are frequently found in commodities, which leads to the trend in the stochastic differential equation that governs the price under the equivalent Martingale measure being $(r - \delta)S_t$, i.e., the riskless rate minus the convenience yield. Wie and Zhu [29] study the convenience yield and the RP in the US natural gas market.

The convenience yield may be nonconstant, may be a deterministic function $\delta(t)$ or may even be modeled as another stochastic process.[6]

In the case of mean reverting model 1 (Inhomogeneous Geometric Brownian Motion (IGBM)[7]) the drift is:

$$k(S_m - S_t) - \lambda S_t = (r - \delta(t))S_t \tag{5}$$

so the convenience yield is variable:

$$\delta(t) = (k + \lambda + r) - \frac{kS_m}{S_t}. \tag{6}$$

In this case when the current price S_t is high the convenience yield is also high.[8]

One of the main reasons that $\delta(t)$ appears can be found in the availability of stocks and inventories of the commodity in question. Everyone who owns inventory has the choice between consumption today and investment for the future. Rational investors will choose the outcome that is best for themselves.

When inventories are high, this suggests an expected relatively low scarcity of the commodity today as compared to some time in the future. Otherwise investors would see no benefit in holding onto inventory and would therefore sell their stocks. Hence, expected future prices should be higher than current prices. Futures or forward prices $F(t, T)$ of the asset should thus be higher than the current spot price, S_t. It is known that

$$F(t, \infty) = \frac{kS_m}{k + \lambda} \tag{7}$$

$$r - \delta(t) = (k + \lambda)\left[\frac{F(t, \infty)}{S_t} - 1\right]. \tag{8}$$

The above formula only reveals that $r - \delta(t) > 0$.

The line of reasoning becomes interesting when inventories are low, in which case scarcity can be expected to be greater now than in the future. Unlike the previous case, the investor cannot buy inventory to make up for demand today. In a sense, the investor wants to borrow inventory from the future but is unable to do so. Therefore future prices can be expected to be lower than today's prices and hence $F(t, T) < S_t$. This implies that $r - \delta(t) < 0$.

Consequently, the convenience yield is inversely related to inventory levels.

6 See the second model in [26].

7 The characteristics of this stochastic model are analyzed in [24].

8 For the case of $S_m = 0$ with $\alpha = -k$ the IGBM becomes GBM and δ is constant: $\delta = (\lambda - \alpha + r)$.

2.5 The Samuelson Effect

Energy futures contracts usually show decreasing volatility as a function of the remaining lifetime of the contract $T - t$, in what is known as the Samuelson effect. As $T - t$decreases, volatility increases and the spot price converges with the futures contract price so that $F(T, T) = S_T$.

2.6 Characteristics of the Models

The behavior of commodity prices may have certain characteristics that must be incorporated into the corresponding stochastic models, depending on the purpose for which they are to be used. Those characteristics include volatility, seasonality, asymmetry, spikes, fat tails and even stochastic volatility.

The model must have a large enough number of parameters but not so many that it acquires a level of additional complexity that is not justified in terms of significant additional descriptive capability.

There is sometimes seasonality in demand, e.g., in the cases of heating oil, natural gas, gasoline and electricity.

2.7 Volatility and Correlations

Volatility is a manifestation of uncertainty. It plays a determinant role in valuing real options. It is usually calculated as the standard deviation of the log of the yields:

$$R_t = \ln\left(\frac{S_t}{S_{t-1}}\right) \tag{9}$$

This gives the value of σ_d to obtain the annualized volatility σ the following is used:

$$\sigma = \sigma_d \sqrt{252} \tag{10}$$

where 252 is the number of trading days. Using spot price data from 12/31/2009 to 08/27/2013[9] this method can be used to calculate the data shown in the second column of Table 1 (without drift). However, it is also possible to work with the residues from the estimate provided by the differential equation. For a case of mean

[9] Source of the original data: http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm.

Table 1 Volatility estimates

Commodity	Without drift	With drift[a]
Crude oil cushing, OK WTI	0.2847	0.2840
New York harbor conventional gasoline	0.3090	0.3082
New York harbor ultra-low sulfur No. 2 diesel	0.2311	0.2305

[a] The drift is the deterministic part of the differential equation. Before the volatility is calculated, the effect of the deterministic trend should be eliminated, but in practice that effect is often very small and volatility can be calculated without this prior adjustment

reversion, using the IGBM differential equation, the following estimate can be drawn up:

$$\frac{S_{t+1} - S_t}{S_t} = -k\Delta t + kS_m\Delta t\frac{1}{S_t} + \sigma\sqrt{\Delta t}\varepsilon_t \tag{11}$$

and with the residues of the differential equation the volatility levels can be estimated, resulting in the figures shown in the third column of Table 1.

As can be seen, in this case the differences are minimal, given that the drift for a small Δt has very little effect.

Figure 1, calculated using the same data source, shows the historical trend in the prices of the commodities in Table 1:

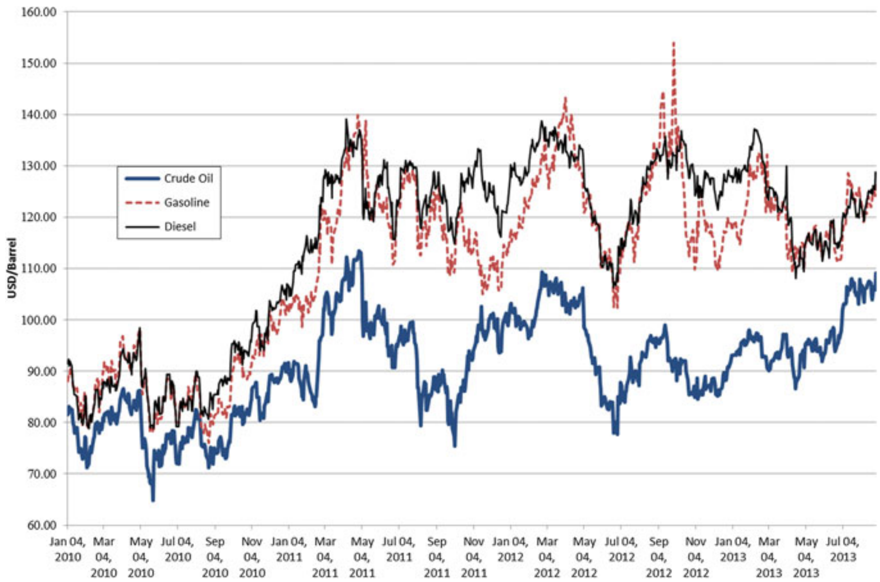

Fig. 1 Historical spot prices of Crude Oil, Gasoline and Diesel

Table 2 Correlations without drift

ρ	Crude oil	Gasoline	Diesel
Crude Oil	1.0000	0.5895	0.7744
Gasoline	0.5895	1.0000	0.6789
Diesel	0.7744	0.6789	1.0000

Table 3 Correlations with drift

ρ	Crude Oil	Gasoline	Diesel
Crude oil	1.0000	0.5872	0.7722
Gasoline	0.5872	1.0000	0.6786
Diesel	0.7722	0.6786	1.0000

Similar approaches can be taken to calculate correlations. If the calculations are based on R_t the figures shown in Table 2 are obtained. If the residues are used, those shown in Table 3 are obtained.

As can be seen, the differences between the results given by the two methods are minimal here too.

With the market data the historical values of a 3:2:1 crack spread can be calculated. The result is shown in Fig. 2.

Volatility can be estimated for an IGBM model, resulting in $\sigma^{\text{IGBM}} = 1.7155$. Observe that in this case $\sigma^{\text{IGBM}} S_t$, appears in the stochastic component of the differential equation, which prevents negative values from being obtained. In the case studied here, an analysis of Fig. 2 shows that there have been no negative values for

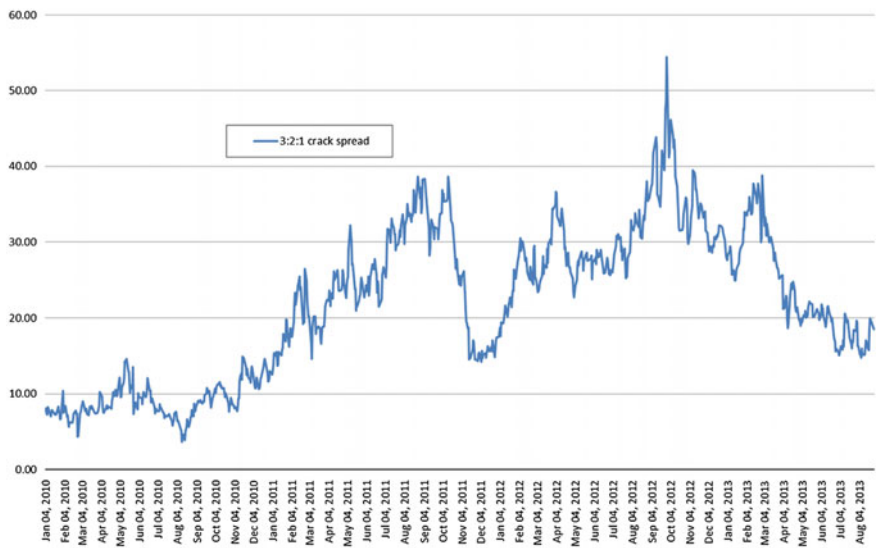

Fig. 2 Historical spot prices for 3:2:1 crack spread

the 3:2:1 crack spread in the series considered. However, if an Ornstein-Uhlenbeck (O-U) process is used, there is no σ multiplied by S_t, which means that the possibility of negative values is admitted. In this case, the estimated volatility is $\sigma^{OU} = 29.1499$, i.e. 17 times greater. Thus, the estimated volatility to be applied in a stochastic process depends on what process is chosen.

3 Commodities Futures Markets

Futures markets provide one of the biggest sources of information for the valuation of investments in energy assets. Since counterparty risk is eliminated, the quotes on such markets are prices in which there is no uncertainty. Thus, the value of—for instance—a barrel of oil for delivery in 2 years time can be discounted at the risk-free interest rate (risk-neutral valuation). This section provides some simple examples using prices from various markets: Light Sweet Crude Oil futures (WTI), NY Harbor ULSD futures, RBOB Gasoline futures, and ICE EUA Futures. The examples include mean reverting processes and GBM, along with cases with and without seasonality.

Futures markets provide information on the values of the parameters in the deterministic part of the differential equation, always in a risk-neutral world. As in the GBM case, the value of $\alpha - \lambda$ can be estimated easily and accurately. The same goes for $\frac{kS_m}{k+\lambda}$ and $k + \lambda$ in the case of the IGBM model. In the case of mean reversion, these markets provide information on the long-term equilibrium value and the rate at which the expected price moves toward that value in the risk-neutral world.

Commodities markets are studied in [10, 12].

3.1 The Case of Light Sweet Crude Oil (WTI) Futures

An example is given below of the calculation of the parameters of a mean reverting process using quotes for Light Sweet Crude Oil (WTI) Futures.

In the case of the IGBM model, the parameters of the following equation are estimated using data from the futures market.

$$F(T_1, T_2) = \frac{kS_m}{k+\lambda} + \left[F(T_1, T_1) - \frac{kS_m}{k+\lambda}\right] \mathrm{e}^{-(k+\lambda)(T_2 - T_1)} \tag{12}$$

This equation can be used to obtain $\frac{kS_m}{k+\lambda}$ and $k + \lambda$ for either an IGBM process or an O-U process. The difference between the two lies in the volatility estimate to be used for the model but this does not affect the above formula.

With the closest futures value, for 8/23/2013, and estimating the parameters in such a way as to minimize the sum of the squares of the differences between the actual future and the estimated figure for each date, the following values are obtained: $\frac{kS_m}{k+\lambda} = 79.5157$ and $k + \lambda = 0.5583.$[10] This calculation is based on the future with the closest maturity (Oct 13), for the date of which the price is $106.42/barrel. As can be seen in Fig. 3, the fit is very close using the values from the two parameters.

From Fig. 3 it is easy to determine that the behavior of this commodity can be modeled via a mean reverting stochastic process.[11]

It is also possible to use the model in [26], where the equation for the future is:

$$F(T_1, T_2) = \mathrm{e}^{[\mathrm{e}^{-k(T_2-T_1)}\ln S_t + (1-\mathrm{e}^{-k(T_2-T_1)})X_m^* + \frac{\sigma^2}{4k}(1-\mathrm{e}^{-2k(T_2-T_1)})]} \tag{13}$$

The results for this case are shown in Fig. 4. The fit is very similar to that of the IGBM case:

The figures obtained in this case are as follows: $\frac{kS_m}{k+\lambda} = 79.5157$ and $k + \lambda = 0.5583$. Modeling here would also be via a mean reverting process. No seasonality is detected in this case.

3.2 The Case of NY Harbor ULSD Futures

This section gives an example of the calculation of the parameters of a mean reverting process using quotes for NY Harbor ULSD Futures.

Figure 5 shows the actual and estimated values on 8/23/2013[12] for ULSD Futures.

In this case the values of the estimated parameters are as follows: $\frac{kS_m}{k+\lambda} = 94.4771$ and $k + \lambda = 0.1556$. No clear seasonal behavior is detected.

3.3 The Case of RBOB Gasoline Futures

This section gives an example of the calculation of the parameters of the seasonal, mean reverting process using quotes for RBOB Gasoline Futures.

Figure 6 shows the actual and estimated values on 8/23/2013[13] for Gasoline Futures.

[10] Quotations from several days could also have been used, but for the sake of illustration the simplest method is preferred here.

[11] The statistical test lies outside the scope of this chapter.

[12] Quotes are converted to $/barrel by multiplying the original $/gallon figures by 42.

[13] Here also the quotes are converted to $/barrel by multiplying the original $/gallon figures by 42.

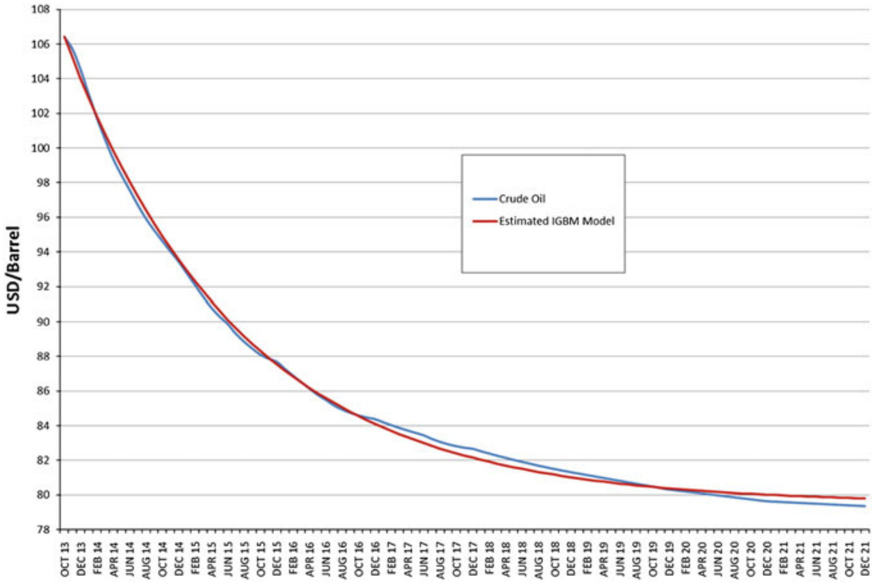

Fig. 3 Crude Oil Futures 08/23/2013 and estimated IGBM Model

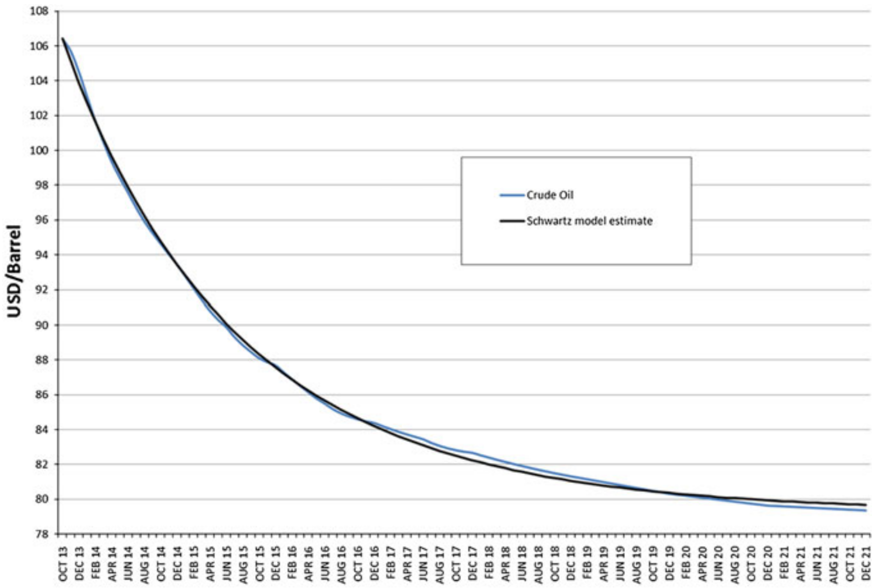

Fig. 4 Crude Oil Futures 08/23/2013 and estimated Schwartz Model

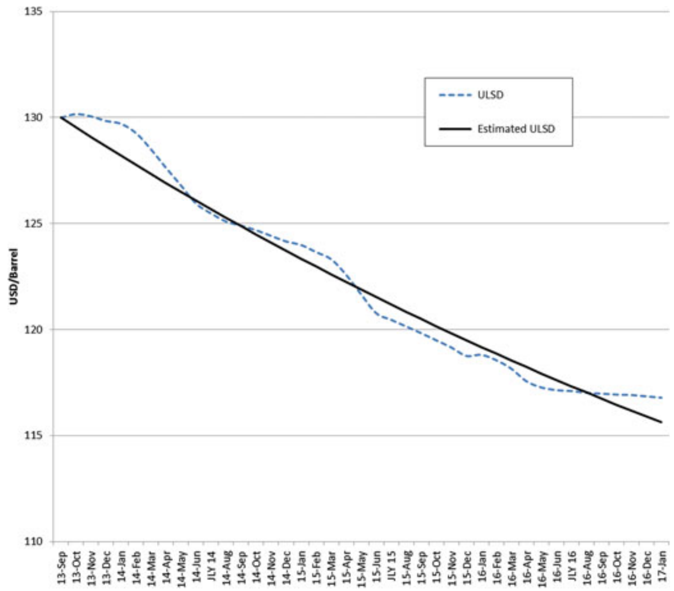

Fig. 5 ULSD Futures 08/23/2013 and estimated IGBM Model

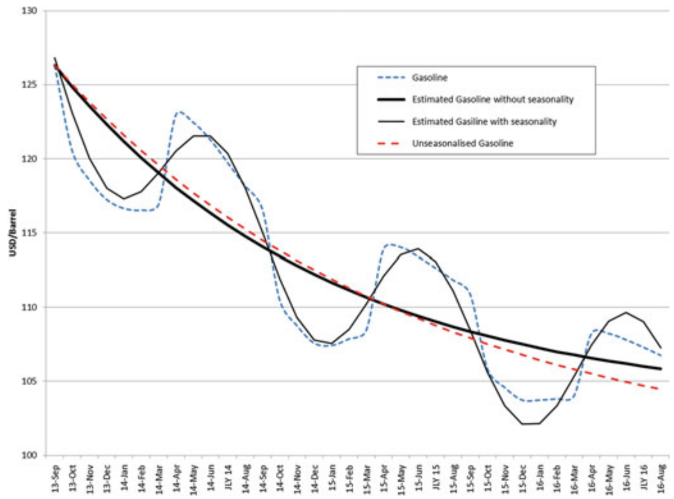

Fig. 6 RBOB Gasoline 08/23/2013 and estimated model

In this case an estimation without taking seasonality into account gives the following values: $\frac{kS_m}{k+\lambda} = 103.3688$ and $k + \lambda = 0.7622$.

However, some degree of seasonality can be seen in the figure. This can be modeled with a deterministic function of the following type: $f(t) = \gamma cos(2\pi(t + \phi))$.

Table 4 RBOB gasoline parameters

Parameter	Value
$\frac{kS_m}{k+\lambda}$	99.5614
$k+\lambda$	0.5814
γ	4.7210
ϕ	0.2329

This leads to the estimation of two additional parameters (Table 4).

The accuracy of the estimate is substantially improved when seasonality is included. Whenever there is seasonality its impact should be considered, but in some cases de-seasonalized series should be worked with. Observe how the estimate of the long-term equilibrium point changes.

4 The Case of ICE EUA Futures

This section gives an example of the calculation of the parameters of a GBM process using quotes for ICE EUA Futures.

Figure 7 shows the ICE EUA Futures quotations for 08/23/2013. As can be seen, these prices behave in a way compatible with GBM-type modeling, where:

$$F(T_1, T_2) = S_t e^{(\alpha-\lambda)(T_2-T_1)} \tag{14}$$

given that this model implies exponential growth in the price of the futures contract as the maturity period increases.

It can clearly be seen in Fig. 7 that the GBM estimate is a better approximation in this case (it is closer to the actual quotation) than the one provided by an IGBM model with these data. Using a GBM model has significant implications in terms of volatility and expected value. Volatility is increasing over time in the risk-neutral world, which significantly affects the calculation of the value of options:

$$\mathrm{Var}(S_T) = S_t^2 e^{2(\alpha-\lambda)(T-t)}[e^{\sigma^2(T-t)} - 1] \tag{15}$$

When volatility is high the value of the option increases significantly.

In the real world, it suffices to set $\lambda = 0$, which gives:

$$\mathrm{Var}(S_T) = S_t^2 e^{2\alpha(T-t)}[e^{\sigma^2(T-t)} - 1] \tag{16}$$

For cases in which T is very close to t the expression obtained is $T = t + \Delta t$

$$\mathrm{Var}(S_{t+\Delta t}) \approx S_t^2 \sigma^2 \Delta t \tag{17}$$

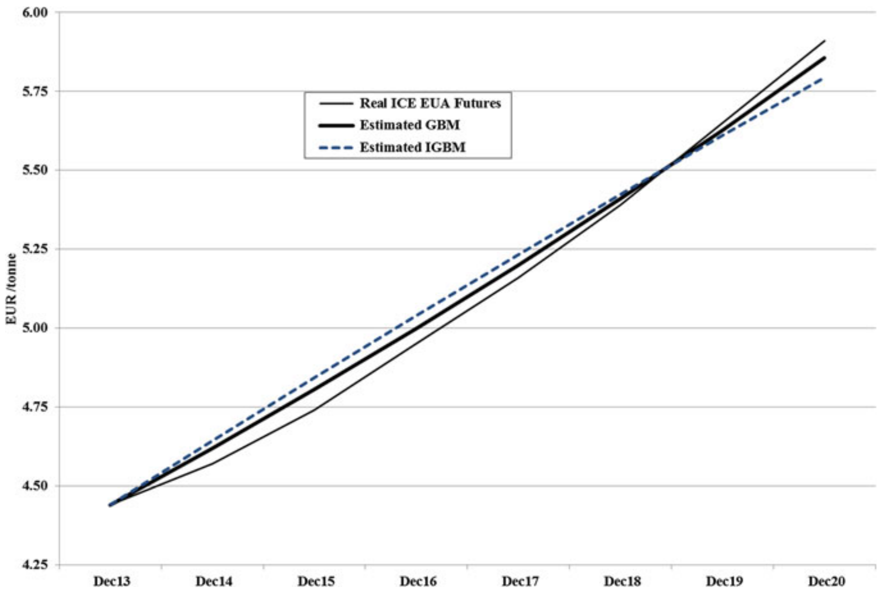

Fig. 7 ICE EUA Futures 08/23/2013

In a GBM model, the expected value increases exponentially instead of moving toward the long-term equilibrium value asymptotically as occurs in mean reverting models.

In the case examined here the estimated value is de $\alpha - \lambda = 0.0395$. In this case, if the convenience yield δ is low $\alpha - \lambda$will be close to the riskless interest rate because of the possibilities of coverage via storage.

4.1 The Case of the 3:2:1 Crack Spread

This subsection combines information from previous subsections to calculate the future value of a 3:2:1 crack spread.

In this case 3:2:1 three barrels of crude oil produce 2 barrels of gasoline and 1 barrel of distillate fuel oil.

These data can be used to calculate the margin per barrel of crude oil:

$$M_T = \frac{2}{3}F^{\mathrm{RB}}(t,T) + \frac{2}{3}F^{\mathrm{HO}}(t,T) - F^{\mathrm{CL}}(t,T) \tag{18}$$

where the superindexes indicate Gasoline (RB), Fuel Oil (HO) and Crude Oil (CL).

In this case the results of the parameter estimation with an IGBM process are in Table 5.

The results for this estimate and the real data are shown in Fig. 8.

Table 5 Parameters for 3:2:1 crack spread

Parameter	Value
$\frac{kS_m}{k+\lambda}$	23.4233
$k+\lambda$	3.0149
γ	2.9776
ϕ	0.3107

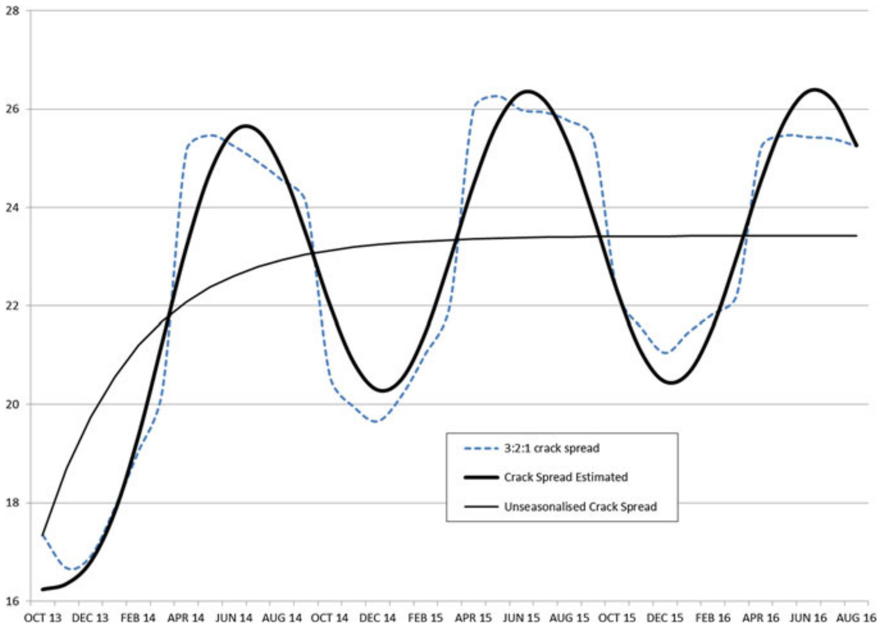

Fig. 8 3:2:1 Crack spread 08/23/2013

5 Marked Based Valuation Methods and Examples

There are various methods for valuing investments, including the NPV, the IRR, the hurdle rate, the payback period, sensitivity analysis, the earning multiple approach, the discounted payback period and ROA. The use of these methods in business is analyzed by Graham and Harvey [15]. This section presents an introduction with examples of market based methods.

5.1 Market Based Valuation Methods

Options in the field of energy are often of the American type, i.e., they can be exercized within a certain period of time. There are analytical solutions for simple cases, and frequently when the option has an infinite lifetime. Dixit and Pindyck [9] analyze some of these cases.

In general numerical methods must be used when real investments are valued. There are three main methods: Binomial Trees, MonteCarlo Simulation and Finite Differences. These methods were originally developed for valuing financial derivatives. Publications describing them and their application to finance include Brandimarte [4], Clewlow and Strickland [8], Hull [17], Luenberger [20] and Wilmott [30].

Publications devoted specifically to valuation methods for real options include Copeland and Antikarov [7] and Trigeorgis [28]. Real options and energy investment are examined in depth in Abadie and Chamorro [1] and Ronn [25]. Pilipovic [22] looks at energy risk management, and Smit and Trigeorgis [27] look at strategic investments with real options and games. The MonteCarlo method for valuing American-type options is also applied in Longstaff and Schwartz [19].

5.2 Examples of Valuations

A number of simple examples are given below:

(A) *Futures flows with price uncertainty*

In this first example, the aim is to determine the NPV of a barrel of oil to be extracted in 2 years time. Possible futures market situations are analyzed, always in a manner consistent with market quotes.

If a barrel of oil is traded on the futures market at \$100 for a 2-year maturity period and the riskless compound interest rate is 3 %, its NPV can be obtained as:

$$\text{NPV} = 100\text{e}^{-2\times 0.03} = \$94.176$$

It must be remembered that the current quotation of the future with maturity in 2 years $F(0,2) = 100$ is not exactly its expected value in the real world in 2 years' time, i.e. $F(0,2) = E_t^Q(S_T) \neq E_t(S_T)$. The situations indicated below may arise, each with its corresponding RP $\text{RP}(0,2)$ values (Table 6).

The futures market is said to exhibit normal backwardation when $E_t(S_T) > F(t,T)$, i.e. when the future is trading below the expected spot price at contract maturity.

The term contango is used to describe the opposite condition, when $E_t(S_T) < F(t,T)$.

Table 6 Example of price uncertainty

$E_t(S_T)$	$RP(0,2)$	μ	$\mu - r$	Market situation
105.00	−5.00	0.0544	0.0244	Normal backwardation
100.00	0.00	0.0300	0.0000	–
95.00	5.00	0.0044	−0.0256	Contango

These values correspond to a different discount rate in the real world. For example for RP $= -5.00$ it must hold that $94.176 = 105\mathrm{e}^{-2\times\mu}$. In general:

$$\mu = -\frac{1}{T-t}\ln\left(\frac{F(t,T)}{E_t(S_T)}\right) \tag{19}$$

As can be seen in the example, when $E_t(S_T) = 105.00$ the discount rate with risk is $\mu = 5.44\ \%$. However it is very hard to estimate $E_t(S_T)$,while $F(t,T)$ is deduced directly from the market quotation. Since the future price $F(t,T)$ is certain,[14] the corresponding amount can be discounted at the riskless interest rate r and the resulting value should be the spot price. The method used is valid assuming that the market is complete.

Now assume that the spot price is $S_t = 97.00$. It is known that:

$$F(t,T) = S_t\mathrm{e}^{(r-\delta)(T-t)} \tag{20}$$

Therefore:

$$\delta = r - \frac{1}{T-t}\ln\left(\frac{F(t,T)}{S_t}\right) = 0.01477 \tag{21}$$

The convenience yield may not be constant, and may vary over time.

(B) *Annuities* (*GBM case*)

In this second example, the aim is to deduce the value of an annuity when the price follows a GBM process, e.g., the price of CO_2 emission allowance over 20 years.

Based on the future equation:

$$F(0,t) = S_0\mathrm{e}^{(\alpha-\lambda)t} \tag{22}$$

An annuity between τ_1 and τ_2 has a value of:

$$V(\tau_1,\tau_2) = \int_{\tau_1}^{\tau_2} S_0\mathrm{e}^{(\alpha-\lambda)t}\mathrm{e}^{-rt}\mathrm{d}t = \frac{S_0}{\alpha-\lambda-r}\left[\mathrm{e}^{(\alpha-\lambda-r)\tau_2} - \mathrm{e}^{(\alpha-\lambda-r)\tau_1}\right] \tag{23}$$

[14] The markets perform the role of covering the counterparty risk.

In the case of S_0 = €4.38, $\alpha - \lambda = 0.0395$, $\tau_1 = 0$, $\tau_2 = 25$, and $r = 0.03$ the result obtained is $V(\tau_1, \tau_2) = 123.60$ €/(tonnes per year). However if si $\delta = 0$ and $\alpha - \lambda = r = 0.0395$ it is $V(\tau_1, \tau_2) = S_0(\tau_2 - \tau_1) = 109.50$/(tonnes per year).

(C) *Annuities* (*IGBM case*)

In this third example, the aim is to deduce the value of an annuity when the price follows an IGBM type mean reverting process, e.g., in the case of a barrel of oil at 1 year over 20 years.

Based on the future equation:

$$F(0,t) = \frac{kS_m}{k+\lambda} + \left[S_0 - \frac{kS_m}{k+\lambda}\right] e^{-(k+\lambda)t} \tag{24}$$

An annuity between τ_1 and τ_2 has a value of:

$$\begin{aligned} V(\tau_1, \tau_2) &= \int_{\tau_1}^{\tau_2} F(0,t) e^{-rt} dt \\ &= \frac{kS_m}{r(\lambda+k)} [e^{-r\tau_1} - e^{-r\tau_2}] + \frac{S_0 - \frac{kS_m}{\lambda+k}}{\lambda+k+r} [e^{-(\lambda+k+r)\tau_1} - e^{-(\lambda+k+r)\tau_2}] \end{aligned} \tag{25}$$

Therefore, the current value of a barrel of oil at 1 year over 25 years between $\tau_1 = 0$ and $\tau_2 = 25$ when $S_0 = 106.42$ USD/barrel, $\frac{kS_m}{\lambda+k} = 79.5157$, $\lambda + k = 0.5583$ and $r = 0.03$ is

$$V(\tau_1, \tau_2) = \frac{106.42 - 79.5157}{0.5883} [1 - e^{-14.7075}] + \frac{79.5157}{0.03} [1 - e^{-0.75}] = 1444.23$$

(D) *Annuities* (*3:2:1 Crack Spread, IGBM case*)

In this fourth example, the aim is to deduce the value of an annuity with a 3:2:1 crack spread over 25 years with market data. The existence of sufficient liquidity in the future market means that these refining margins can be assured.

Leaving aside the effect of seasonality, since periods of higher prices tend to be offset by periods of lower prices, the current value of a unit with 3:2:1 crack spread at 1 year over 25 years between $\tau_1 = 0$ and $\tau_2 = 25$ when $S_0 = 17.3456$ USD/ barrel, $\frac{kS_m}{\lambda+k} = 23.4233$, $\lambda + k = 3.0149$ and $r = 0.03$ is

$$V(\tau_1, \tau_2) = \frac{17.3456 - 23.4233}{3.0449} [1 - e^{-75.3726}] + \frac{23.4233}{0.03} [1 - e^{-0.75}] = 409.97$$

Table 7 Crude Oil (CL) and Fuel Oil (HO) parameters

Parameter	CL	HO
S_0	106.42	130.158
$\frac{kS_m}{k+\lambda}$	79.5157	94.4471
$k+\lambda$	0.5583	0.1556
σ	0.2840	0.2305

This valuation assumes that production is always $\frac{2}{3}$ of a barrel of Gasoline and $\frac{1}{3}$ of a barrel of fuel oil from one barrel of crude oil. This is the case if the plant is operational at all times and the crack spread is always positive.

In practise things are not that simple: there are also fixed costs and other variable costs. In this case, a number of MonteCarlo simulations of the stochastic process could be run, with the maximum between the crack spread minus the variable costs and zero being obtained in each case and with the results being discounted at the riskless rate. This serves to determine the average current value, from which the amount of the current fixed must be discounted.

(E) *Stochastic process simulation*

This example involves a MonteCarlo simulation. The aim is to demonstrate that the goodness of the simulation can be checked by checking the resulting volatilities and correlations against originals from the stochastic model.

Two correlated stochastic processes are simulated below using the Table 7 parameters:

Initially we have:

$$\Delta S_t^i = \frac{k^i S_m^i}{k^i + \lambda^i} + \left[S_{0'}^i - \frac{k^i S_m^i}{k^i + \lambda^i}\right] \mathrm{e}^{-(k^i+\lambda^i)\Delta t} + \sigma^i S_t^i \sqrt{\Delta t}\,\varepsilon_t^i \tag{26}$$

where $i \in \{\text{CL, HO}\}$

Along with the correlation $\rho_{CL,HO} = 0.7222$.

The correlated samples are obtained by applying the following:

$$\varepsilon_t^{\text{CL}} = \mathrm{e}^{\text{CL}}$$

$$\varepsilon_t^{\text{HO}} = (\mathrm{e}^{\text{CL}} \rho_{\text{CL,HO}} + \mathrm{e}^{\text{HO}} \sqrt{1 - \rho_{\text{CL,HO}}^2}) \tag{27}$$

where e^{CL} and e^{HO} are uncorrelated random samples.

A simulation is conducted at 25 years with 252 steps per year for both crude oil (CL) and fuel oil (HO). It can be observed that the volatilities estimated from the simulation would be very similar to the model parameters. These results are shown in Table 8.

The estimated correlation is 0.7229. Volatility estimations and correlation can therefore be regarded with confidence.

Table 8 Crude Oil (CL) and Fuel Oil (HO) parameters estimated with simulation

Parameter	CL	HO
σ	0.2821	0.2298

6 Conclusions

This chapter deals with issues that are significant for the valuation of investment in energy assets when the Real Option Approach (ROA) method is used, combined with stochastic differential equations for the prices of the commodities, the parameters of which are estimated using market quotations. A description is given of the conditions that must exist for this valuation technique to be able to be used correctly. An analysis is also given of the characteristics of the prices of the commodities traded on energy markets, with particular emphasis on mean reversion, the convenience yield and seasonality.

A simple method is also presented for estimating the parameters of the corresponding stochastic differential equations using real market data and the 3:2:1 crack spread is examined. The data obtained are used in some simple, illustrative examples.

The chapter ends with an appendix that gives more details of the properties of the stochastic processes used.

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Appendix: Stochastic Models for Energy Investments

Stochastic models for valuing energy assets must take into account the most significant characteristics of each commodity, i.e. volatility, asymmetry, spikes, fat tails and stochastic volatility among others. However models should have sufficient parameters but not so many that they acquire a level of additional complexity that is not justified in terms of significant additional descriptive capability. Models differ depending on whether they seek to value a derivative in the short term or a long-term investment. Two basic elements that appear frequently in energy commodities are (a) the seasonality caused by alterations in demand (e.g., for heating in winter and air conditioning in summer), which may depend on geographical location; and (b) mean reversion. However, in a long-term investment decision seasonality has little influence and does not determine the production strategy (it is relatively unimportant in valuing a base load power plant, though it may be more significant in valuing a peak power plant) [3].

Gourieroux and Jasiak [14] examine the estimation of the parameters of certain stochastic differential equations.

The characteristics of four stochastic processes are described below: a GBM model and three mean reverting models.

A.1 Geometric Brownian Motion Model

This model is not widely used in modeling the behavior of commodity prices (which in turn can determine the value of investment in energy assets) because it is considered that the prices of these commodities tend to show mean reverting behavior, especially when futures market quotations are analyzed.

In the real world, the model is as follows:

$$dS_t = \alpha S_t dt + \sigma S_t dW_t \tag{28}$$

where S_t is the price of the commodity at time t, α is the drift in the real world, σ is the instantaneous volatility and dW_t stands for the increment to a standard Wiener process.

The risk-neutral version of the model is:

$$dS_t = (\alpha - \lambda) S_t dt + \sigma S dW_t \tag{29}$$

where λS_t is the market price of risk.[15]

It holds that $\alpha - \lambda = r - \delta$ with r being the riskless rate and δ the convenience yield, so the following alternate expression can also be used:

$$dS_t = (r - \delta) S_t dt + \sigma S dW_t \tag{30}$$

If $X = \ln S$, and Ito's lemma is applied, then the following is obtained:

$$dX_t = \left(\alpha - \lambda - \frac{\sigma}{2}\right) dt + \sigma dW_t \tag{31}$$

In this case it the value of a future with maturity T at time t is obtained from the following equation:

$$F(t, T) = S_t e^{(\alpha - \lambda)(T - t)} = S_t e^{(r - \delta)(T - t)} \tag{32}$$

Equation (32) shows that a commodity with GBM-type behavior in the spot price should exhibit quotations on the futures market that increase in absolute value

[15] Kolos and Ronn [18] estimate the market price of risk for energy markets.

by larger amounts as the maturity period increases. This behavior can be used to identify whether a commodity is a good candidate for modeling with GBM.

In the real world:

$$E_t(S_T) = S_t e^{\alpha(T-t)} \quad (33)$$

So the RP looks like this:

$$\mathrm{RP}(t,T) = F(t,T) - E_t(S_T) = S_t e^{\alpha(T-t)}[e^{-\lambda(T-t)} - 1] \quad (34)$$

Thus:

(a) if $\lambda = 0$ then $F(t,T) = E_t(S_T)$ and $\mathrm{RP}(t,T) = 0$. In this case the future is an unbiased estimator of the expected spot price.
(b) if $\lambda > 0$ then $\mathrm{RP}(t,T) < 0$. In this case the future is a downward-biased estimator of the spot price.
(c) if $\lambda < 0$ then $\mathrm{RP}(t,T) > 0$. In this case the future is an upward-biased estimator.

The sign of the RP and the sign of the market price of risk are exactly opposite. Moreover, assuming a market price of risk that is constantly proportional to the spot price, the RP tends to zero as the time t approaches the maturity T. This means that the future is a good estimator for close-at-hand maturity times, because even though it is biased the bias may be slight. The same cannot be said of more remote maturity times, where the bias may be significant.

Observe that the following is also valid from two futures contracts with maturities T_1 and T_2 onwards:

$$F(t,T_2) = F(t,T_1)_t e^{(\alpha-\lambda)(T_2-T_1)} \quad (35)$$

In some cases, this may make it possible to do away with the use of the spot price S_t, which may sometimes not be observable.

A.2 Inhomogeneous Geometric Brownian Motion Model

This is a mean reverting model that has the following stochastic differential equation:

$$dS_t = k(S_m - S_t)dt + \sigma S_t dW_t \quad (36)$$

where S_t is the price of the commodity at time t, k is the reversion rate, S_m is the expected price to which the value of the commodity tends in the long term, σ is the instantaneous volatility and dW_t stands for the increment to a standard Wiener process.

Under the equivalent Martingale measure this can be expressed as:

$$\mathrm{d}S_t = [k(S_m - S_t) - \lambda S_t]\mathrm{d}t + \sigma S_t \mathrm{d}W_t \tag{37}$$

where the market price of risk (MPR) is proportional to S_t.

The expected value at a time T can be calculated as follows:

$$\frac{E(\mathrm{d}S_t)}{\mathrm{d}t} + (k + \lambda)E(S_t) = kS_m \tag{38}$$

This can be solved by using $\mathrm{e}^{(k+\lambda)t}$ as an integration factor, which gives:

$$E_Q(S_t) = \frac{kS_m}{k + \lambda} + C_0 \mathrm{e}^{-(k+\lambda)t} \tag{39}$$

where C_0 is a constant determined as a function of the initial conditions. Since it must hold that $E_t(S_t) = S_t$ the following is obtained:

$$C_0 = S_t - \frac{kS_m}{k + \lambda}$$

$$F(t, T) = \frac{kS_m}{k + \lambda} + \left(S_t - \frac{kS_m}{k + \lambda}\right)\mathrm{e}^{-(k+\lambda)(T-t)} \tag{40}$$

It is easy to check that formula (40) complies with the differential equation. It can also be checked that this solution complies with the differential equation:

$$\frac{1}{2}\sigma^2 S^2 F_{SS} + [k(S_m - S_t) - \lambda S_t]F_S = F_T \tag{41}$$

with the terminal condition $F(t, t) = S_t$

where the subindexes of Frefer to the derivatives corresponding to future Eq. (40).

The expected future value of the spot price for the mean reverting model can easily be obtained from Eq. (40) by assuming $\lambda = 0$. It works out to:

$$E_t(S_T) = S_m + (S_t - S_m)\mathrm{e}^{-k(T-t)} \tag{42}$$

The RP is:

$$\mathrm{RP}(t, T) = F(t, T) - E_t(S_T) \tag{43}$$

In this case a high reversion rate $k$reduces the RP.

Observe also that for a very long-term future the expected real-world value is precisely S_m:

$$E(S_\infty) = S_m$$

and

$$F(t, \infty) = \frac{kS_m}{k + \lambda}$$

Therefore,

$$\text{RP}(t, \infty) = \frac{-\lambda S_m}{k + \lambda}$$

If this model is fully representative of the actual behavior of a futures market long-term quotations provide information on $\frac{kS_m}{k+\lambda}$, which is linked to the MPR such that when $\lambda = 0$, $F(t, \infty) = S_m$ is obtained, and if the reversion rate is very high then the RP is low.

Consider two contracts T_1 and T_2. The following is obtained:

$$F(t, T_1) = \frac{kS_m}{k + \lambda} + \left[S_t - \frac{kS_m}{k + \lambda}\right] \mathrm{e}^{-(k+\lambda)(T_1 - t)}$$

$$F(t, T_2) = \frac{kS_m}{k + \lambda} + \left[S_t - \frac{kS_m}{k + \lambda}\right] \mathrm{e}^{-(k+\lambda)(T_2 - t)}$$

It can be deduced that

$$F(t, T_2) = \frac{kS_m}{k + \lambda} + \left[F(t, T_1) - \frac{kS_m}{k + \lambda}\right] \mathrm{e}^{-(k+\lambda)(T_2 - T_1)} \tag{44}$$

The GBM model is a particular case of this model when $S_m = 0$ and $\alpha = -k$ for this case:

$$F(t, T)_{\text{GBM}} = S_t e^{(\alpha - \lambda)(T - t)} \tag{45}$$

which is the same result as obtained above.

A.3 The Schwartz Model

The Schwartz model is implemented, but with a different specification of risk as λS_t in the differential equation for the spot price under the equivalent Martingale measure.[16]

Start from:

$$dS_t = k(\mu - \ln S_t)S_t dt + \sigma S_t dz_t \quad (46)$$

the risk-neutral version of which with the modeling of the market price of risk selected is:

$$dS_t = [k(\mu - \ln S_t)S_t - \lambda S_t]dt + \sigma S_t dz_t^* \quad (47)$$

With $X_t = \ln S_t$ the model takes the following form:

$$dX = \left[k(\mu - X) - \lambda - \frac{\sigma^2}{2}\right]dt + \sigma dz_t^* \quad (48)$$

with $X_m^* = \mu - \frac{\sigma^2}{2k} - \frac{\lambda}{k}$

$$dX_t = k(X_m^* - X_t)dt + \sigma dz_t^* \quad (49)$$

from which the future equation is obtained as:

$$F(t,T) = e^{[e^{-k(T-t)}\ln S_t + (1-e^{-k(T-t)})X_m^* + \frac{\sigma^2}{4k}(1-e^{-2k(T-t)})]} = e^{[\bullet]} \quad (50)$$

and, as can be checked, $F(t,t) = S_t$.

A.4 The Ornstein-Uhlenbeck (O-U) Process

The differential equation for this stochastic process is:

$$dS_t = k(S_m - S_t)dt + \sigma dW_t, \quad (51)$$

where S_t denotes the price at time t. This current value tends to the S_m level in the long term at a reversion rate k. $\sigma$is the instantaneous volatility, and dW_tstands for the increment to a standard Wiener process.

This model allows $S_t$to take both negative and positive values. The price has a conditional mean

[16] In the original model by Schwartz [26] this appears as a risk premium for the log of the price.

$$E(S_t) = S_0 e^{-k_S(t-t_0)} + S_m(1 - e^{-k_S(t-t_0)}), \tag{52}$$

which amounts to

$$E(S_{t+\Delta t}) = S_t e^{-k_S \Delta t} + S_m(1 - e^{-k_S \Delta t}). \tag{53}$$

Also, the conditional variance is

$$\mathrm{Var}(S_t) = \frac{\sigma_S^2}{2k_S}[1 - e^{-2k_S(t-t_0)}]. \tag{54}$$

Since both mean and variance remain finite as $t \to \infty$, this process is stationary.

Equation (11) is the continuous-time version of a first-order autoregressive process AR (1) in discrete time:

$$S_{t+\Delta t} = S_m(1 - e^{-k\Delta t}) + S_t e^{-k\Delta t} + \varepsilon_{t+\Delta t} = a + bS_t + \varepsilon_{t+\Delta t}, \tag{55}$$

where $\varepsilon_t : N(0, \sigma_\varepsilon)$, and the following notation holds:

$$a \equiv S_m(1 - b) \Rightarrow S_m = \frac{a}{1 - b}, \tag{56}$$

$$b \equiv e^{-k\Delta t} \Rightarrow k = -\frac{\ln b}{\Delta t}. \tag{57}$$

Also

$$(\sigma_\varepsilon)^2 = \frac{\sigma^2}{2k}[1 - e^{-2k\Delta t}] \Rightarrow \tag{58}$$

$$\Rightarrow \sigma^2 = \frac{2k(\sigma_\varepsilon)^2}{1 - e^{-2k\Delta t}} = \frac{2(\sigma_\varepsilon)^2 \ln b}{\Delta t[b^2 - 1]}.$$

Equations (56–58) enable the continuous-time process parameters (k, S_m, σ) to be recovered on estimating the regression coefficients (a, b) and the standard deviation of the regression residuals (σ_ε).

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Part II
Energy Efficiency

Policy Instruments to Foster Energy Efficiency

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Abstract In this chapter we start by enumerating the reasons why progress in realizing the energy efficiency potential has been so limited both for firms and households. Then we turn to the role of policy in moving agents closer to an optimal level of energy efficiency. Governments have a range of instruments at their disposal for doing so and while some of them have been successful others have not. Lessons can therefore be learnt from the experience in implementing these different measures. The paper ends with some thoughts on how policies can be made more effective.

1 Introduction

An important part of the actions required to move to a low carbon economy is an increase in the amount of economic output we get out of a unit of energy—i.e. an increase in energy efficiency. A recent report from the European Parliament for climate end energy policies [24] notes that the EU has a cost-effective potential for energy saving achieved through energy efficiency of 40 % in the whole economy (61 % from the residential sector, 41 % from transport, 38 % from the tertiary sector, and 21 % from industry). It also notes that a significant percentage of this has not been realized—80 % in the case of the residential sector and 50 % in the

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case of industry. This difference between the real level of investment in energy efficiency and the "economically optimal level" as defined in various studies such the one mentioned above is referred to in the literature as the Energy Efficiency Paradox [48].

In this chapter we focus on the reasons why progress in terms of realizing the energy efficiency potential has been so limited. To being with we consider why individuals and firms do not take advantage of the benefits of increased energy efficiency. Then we turn to the role of policy in moving agents closer to the optimal level. Governments have a range of instruments at their disposal for doing so and while some of them have been successful others have not. Lessons can be learnt from the experience in implementing these different measures. The chapter finishes with some thoughts on how policies can be made more effective.

2 How Rational Are Individuals in Their Use of Energy?

At the outset it helps to define the economically optimal level of energy efficiency more precisely. From an economic perspective measures should be pursued to increase energy efficiency to the point at which the costs of further efforts in improving it are equal to the benefits. In this definition the costs are to be seen as the social costs and the benefits as the social benefits (as opposed to the private costs and benefits). This distinction is important because an individual will only seek to achieve efficiency to the point at which private costs and benefits are equalized. The social and private benefits diverge because energy use creates externalities such as local and global air pollutants. So even if the agents in an economy were to realize their full net gains from such actions they would not undertake enough effort in increasing energy efficiency.

But in practice agents do not even equate the private benefits of more efficient energy use to the costs and understanding the reasons for that are important. Why do we not, for example, switch off devices such as TVs when the savings in energy are significant and costs minute? Or buy energy efficient light bulbs when all calculations indicate that they are more cost effective than incandescent ones? Indeed, researchers have found that individuals discount the future very highly and that the estimates of energy efficient choices are based on lower rates. Studies of choices for energy efficient refrigerators in US, for example, indicate that consumers' mean discount rate is about 39 %, with a normal distribution around that mean, and standard deviation of 18.7 [64]. The literature gathers these situations under the so-called Energy Efficiency Paradox, and provides a number of reasons that explain it (see e.g. [52]). First perhaps is the fact individuals are not always rational. When facing difficult decisions we apply simplified approaches that are easy to implement. Acting rationally can involve a lot of information processing and when the costs of dealing with the many decisions are taken into account some of the so-called non-rational actions look rational [39].

Other factors that can explain the apparent lack of even limitedly optimal self-interest behavior at the individual level include: (a) lack of knowledge about energy saving measures (b) capital constraints, which make it difficult to acquire equipment that is more energy efficient[1] (c) time preference (d) the principal-agent problem and (e) uncertainty about the effectiveness of the measures.[2] These points have been discussed a lot in the literature, going back to the Jaffe and Stavins [48] paper and need not be repeated again in detail. Perhaps a few words may be said about some of the less well-known ones. Some studies have focused recently on estimating the existence and the magnitude of the principal-agent problem [13]. This situation happens, for example, in the case where renter decisions about energy use are taken by her and she pays the bills but the decisions about the equipment installed are taken by the owner, who goes for the cheapest alternative. Thus, in this case the most cost efficient combination may not be chosen [43].

In terms of policy the implications from this literature are clear at least in terms of what we need to change. Better information, possible access to up-front capital, loans at subsidized rates and regulations that specify efficiency standards in certain cases emerge as possible measures. These have been tried to various degrees and we discuss them in the later sections. Another line of reasoning that has been followed is to change some less rational behavior through "nudges" and other measures where we appeal to other factors. These can include the following:

- Smart meters: provide more information on use and allow you to program use accordingly.
- Comparison with neighbors about use rates (how you compare with the average and with the most efficient).
- DIY meter that glows if you are using more energy than normal (UK).
- Power aware cords for appliances. They glow if a light has been left on for long.

There is limited anecdotal evidence but no full review of how effective such measures are (except work on smart meters which questions their cost effectiveness, see e.g. [15]). Indeed given the limited evidence on the effectiveness of such measures their popularity in some public debates about the way forward may be, in our view, misplaced.

[1] Surveys carried out by the OECD and others indicate that economic considerations such as the full price (i.e. levelised costs including capital plus operating costs) are not as important as capital costs and labelling of products when making energy appliance choices [68].

[2] There is also a literature which notes that measures of the energy paradox are exaggerated because the methods used do not take account of the fact that consumers have different preferences. See for example, [7].

3 Measures to Improve Energy Efficiency

The discussion in the previous section leads us to consider the different instruments for improving energy efficiency and getting as close as possible to the socially optimal level. As noted, this requires more than getting individuals to achieve their private optimality goals. The presence of externalities means that further increases in efficiency are justified.

Summaries of the research on energy efficiency policies can be found in a number of publications (see for example [23, 37, 44, 45, 46, 60]). What this chapter offers in addition is: (a) an update from recent publications on instruments and (b) our interpretation of the areas where the conclusions are perhaps misleading and where we need further work.

The policies and measures at our disposal can be put into broadly three categories. The first consists of direct intervention through public policies that establish minimum standard levels and mandate certain technical requirements that increase energy efficiency. The second are the group of instruments that work through 'price' incentives, e.g. in the form of subsidies or charges or other financial costs of energy to the consumer or producer. Lastly we have schemes that seek to improve knowledge of energy related issues, such as use of appliances, existence of efficient methods of using energy etc. Table 1 shows examples of each policy carried out by several European countries.

3.1 Command and Control Approaches

Governments can require manufacturers to produce energy products and services with a minimum level of energy performance. Usually these policies are implemented through codes and standards. Some examples are construction codes for building sector, minimum standards for automobiles and appliances, or small-scale combustion plans for industrial sector. These legislative or normative measures are characterized by their low flexibility, which in some cases can generate considerably high implementation costs [31]. The rigidity originated by the absence of any alternative in the market can make some agents, for whom the costs of applying such measures are very high, to leave the market. Consequently, governments should carefully determine the minimum level that achieves the maximum savings at the lowest cost for the whole society.

3.2 Price Instruments

In contrast with command-and-control measures, price or economic instruments have the objective to encourage or discourage certain economic decisions by

Table 1 Summary and examples of the most common energy efficiency policies in Europe

Classification	Energy efficiency policy	Example	Country	Sector
Command-and-control	Codes	Building codes	France	Household, Tertiary
	Standards	Emission performance standards for new passenger cars	Germany	Transport
Price instruments	Taxes	Motor vehicle duty (with CO_2-based components since 2009)	Germany	Transport
	Subsidies	CHP grants program (private sector)	Ireland	Tertiary
	Tax deductions	VAT deduction in energy efficiency investment	France	Household
	Credits	Energy saving loans	Norway	Household
	Permits	EU-ETS	Germany	Industry
	Tradable obligations	White certificates	Italy	Household, tertiary, industry
Information instruments	Labels	Energy performance certificates for buildings	Spain	Residential, tertiary
	Audits	Compressed air efficiently—the PATE audit model	Finland	Industry
	Smart meters and billing information	Smart metering and billing for SMEs	UK	Household tertiary

Source Project ODYSSEE-MURE

indirect changes in prices. Thus, public authorities can use taxes and permits to penalize energy consumption, and subsidies and tax deductions to stimulate energy savings. They are usually applied on CO_2 emissions or energy consumption but may also take the form of tax relief on appliances, loans at preferable rates etc. Although these measures are also subject to important limitations, they are characterized by a higher degree of flexibility in the way that the energy sector can respond to the measure.

Taxes have traditionally been one of the most common instruments used by energy and climate change policies to control energy consumption. They have been mainly applied directly on consumption, and one of their advantages is the capacity to generate tax revenues that can be then redirected with energy efficiency and distributional purposes. Some examples of taxes are acquisition taxes for automobiles and electricity and fossil fuels taxes in the residential sector. At the same time, governments have also introduced a large variety of direct subsidies and tax deductions for energy efficiency investments in all sectors of the economy.

Moreover, some governments have also approved low interest loans to help financing such investments, and particularly ESCOs.[3]

As noted these interventions are also exposed to important limitations. First, in many cases they raise energy prices, which are politically sensitive, partly due to our experience of the volatility in oil and gas markets. There is a major concern about energy (or fuel) poverty that limits the scope for increasing prices as a policy tool, although there is also evidence that the impacts of some increases on income distribution are exaggerated. In developing countries the case for fuel taxes is opposed on distributional grounds but as Sterner [72, 73] has forcefully shown the main beneficiaries of lower prices are not the poor but middle and upper income groups. It is also argued in the literature that the impact of raising energy prices on energy consumption is small as the price elasticity for different kinds of energy is very low in the short run and general low in the long run [38]. The evidence on this, however, is contested. While most researchers would agree that the short-run demand is inelastic with respect to price there is some evidence that in the long run the elasticity is considerable and often well over one [72]. Moreover the estimates have a wide range, indicating that response to taxes may well vary by location [26].

The other fiscal incentive of course is to provide some kind of subsidy and there are many schemes of this kind that have been tried. In general they do result in the adoption of more energy efficient appliances and they are politically popular but they have a number of negative aspects. One is the high fiscal cost of providing the subsidy. Second is the scope for misuse of funds when a subsidy is being offered. Third we have the rebound effect, so the reduction in the price of an appliance results in consumers buying larger and more energy-using versions. For all these reasons subsidies often turn out to be a high-cost policy for achieving energy efficiency [49]. We provide a more detailed comparison between taxes and subsidies in the next section.

A dual approach to fiscal incentives is to use permits rather than taxes and subsidies and there a number of cases of such approaches in Europe and the US, the largest perhaps being the EU emission trading scheme (EU ETS) for GHG emissions created in 2003. By limiting the number of allocated permits the authorities can reduce emissions and provide incentives to increase energy efficiency. Since the permits are tradable, agents with a low cost of reducing emissions can make bigger cuts then their allowances demand and sell any surplus to those agents who face higher costs. In this way the overall cost of meeting a given target reduction is minimised. The EU ETS is discussed elsewhere and we do not go into depth on it, except to note that its effectiveness in including energy efficiency gains is clearly dependent on how many permits are issued, on how they affect energy prices and by the interaction between the ETS and other schemes. The EU ETS has been

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[3] Energy Services Companies (ESCOs) are companies that guarantee the energy savings by energy performance contracting, that is, customers pay the services with the energy savings achieved.

facing significant problems that are related to the preceding matters but, as indicated above, they are beyond the objectives of this chapter.

The use of trading to allocate efficiency targets has been deployed in other contexts of energy regulation as well. One of the latest and most innovative policies to promote energy efficiency is the introduction of obligations or white certificates systems. This legislative measure requires energy suppliers to achieve a fixed amount of energy saving by applying certain measures of energy efficiency on their final customers, during a limited period of time. In some cases, the level of energy savings is certified by public authorities through the so-called white certificates, which can be traded so an overachievement of a target can be sold to someone who is under achieving his target. Hence, similarly to permits, obligation systems represent a flexible approach that encourages cost effectiveness.

This mechanism has been applied recently in Italy, UK, France, Denmark and the Flemish region of Belgium. The design of the policy varies for each country depending on the obliged party, the number of involved sectors, and on the measurement of energy savings. Bertoldi and Rezessy [8] and Bertoldi et al. [9] provide a detailed description of such systems. While there are many positive aspects to such an approach, there has been concern with the possible interactions with the EU-ETS in Europe, and with the existence of rebound effects (see below).

3.3 Information Instruments

Information policies have the goal of mitigating the negative effects of incomplete information, one of the most important market failures in this area. During the last few years governments and energy agencies have introduced a number of different mechanisms to provide customers with direct, cheap and reliable information about the energy performance of their energy services and products. Some examples of these were presented in the previous section (see Sect. 2).

Such information can be provided in different formats, depending on the sector of the economy. One of these is energy performance certificates or labels, which were first used in other areas such as the food industry. More recently, they were used in the energy efficiency market for products like vehicles, buildings, or appliances. These labels or certificates have the objective to provide consumers with information regarding the energy performance of such products. Most importantly, they generally classify that level of energy performance in relation to the rest of products in the market so that consumers can then compare them. In the US the *EnergyStart* is a voluntary program that distinguishes high-energy performance products such as buildings, appliances, electric equipment, etc. In Europe, the Energy Performance of Buildings Directive (Directive 2010/31/EU) [18] requires the owner to show an energy performance certificate when any building is rented or sold. Directives 1999/94/CE [19] and Directive 92/75/CEE [20] revised in 2010 (Directive 2010/30/EU) [21] replicate this with vehicles and appliances, respectively.

Regarding the industrial sector, the most common information instrument is energy audits. Some governments perform free-of-charge energy audits for a group of industries with the objective to spread the results among the correspondent industrial branch, while others simply help in partly financing energy audits.

Finally, as noted in the previous section, some governments and regulatory commissions are also approving specific legislation to guarantee the introduction of other innovative informational mechanisms that have been found to achieve some energy savings in the residential sector. In particular, these mechanisms consist of smart meters that help consumers to know their own consumption in real time, and billing information that includes a comparative analysis of their own consumption with that of a similar consumer. In particular, billing information uses social norms to change the habits or behavior of consumers towards more energy-responsible patterns [69]. The following section shows some examples of this approach.

4 Evaluating the Effects of Policies

In this section we present some of the key findings relating to the effectiveness of the different policies described above. Given that a number of them have only recently been introduced it is not possible to undertake a comprehensive ex post assessment and the jury is still out as to how effective they are. In such cases we can only comment on issues relating to the implementation of the programs and on some surveys that have been conducted during implementation.

4.1 Codes and Standards

Since codes and standards have been applied for many years, the market has already generated a sufficient amount of data that allows analysts to evaluate these policies ex post, using real data.

In the case of transport, the data show that despite the improvements on fuel consumption levels due to standards, final energy consumption from transport sector has continued growing due to an increase of the size of vehicles that have outweighed the previous effect [78]. The rebound effect is thus particularly important here and estimates indicate that a 100 % increase in energy efficiency can result in an increase of about 22 % in energy demand [71]. Other authors such as Frondel et al. [28] find even higher rebounds, in the 50–60 % range.

In the residential sector the evidence of such an effect is much less clear. Aroonruengsawat et al. [4] found that those states in the US that had adopted building codes before an increase in construction had reduced their per capita electricity consumption from 0.3 to 5 % in 2006. Other studies find mixed evidence on the effectiveness of the measures in terms of reductions in energy [71].

While several studies measure this rebound effect very few carry out a cost effectiveness analysis of the codes and measures that improve efficiency: how much did the standards raise costs of energy and how much was the cost per unit of energy saved? Moreover, where they do carry out the studies some elements of the cost of making the reduction are ignored (such as costs of changing practices, procedures etc.).

The literature also shows that the largest effects of these instruments could be obtained in developing countries, where the stock of buildings is still growing. Iwaro and Mwasha [47] survey 60 counties from Africa, Latin America and Middle East, and suggest that despite the growth in the number of standards during last years and some improvement in energy efficiency, most of them are far from the minimum level required in industrialized countries.

Finally recent reviews of the literature on standards shows that instruments such as energy efficiency standards (e.g. Energy Performance of Buildings Directive) have been one of the main drivers of innovation [58]. The literature also suggests that public R&D financing plays an important role in innovation as compensation for underinvestment in the private sector [63].

4.2 Fiscal Instruments

Energy taxes also have a long history that has raised a multitude of ex post empirical evaluations from the different policy initiatives introduced by governments all around the world. The transport sector is one of the preferred targets for tax policies (there are not many precedents of energy efficiency taxation in the residential sector), in particular road transport, which represents nearly 70 % of the CO_2 emissions from transport. The most common taxes used in this sector are fuel taxes, taxes on vehicle purchase and annual property taxes (the last two are usually based on different attributes of the vehicle). The final goal of these policies can be revenue raising, environmental or related to energy dependence (see [33]). In the European Union purchases and property taxes have been shifting from taxing engine power or size to CO_2 emissions or fuel consumption. For an overview of the existing research in this area see Ryan et al. [65]. The effect of such taxes on energy demand is well established: witness the difference in car engine size and fuel consumption between North America where fuel taxes are low and Europe where they are much higher.

The cost effectiveness of tax schemes is less well researched. We know that there are welfare losses associated with taxes but how much are we paying in terms of such losses per unit increase in energy efficiency? A study by Markandya et al. [53] looked at this question for a policy of increase in energy taxes and found in general that the cost per ton of CO_2 reduced in selected European countries was negative in the case of energy savings from refrigerators, water heaters and light bulbs. This cost included the traditional welfare cost to consumers as well as administrative costs of implementing the tax and welfare gains to producers of more expensive equipment. Thus a tax option at least in this context looks like an attractive option for increasing energy efficiency.

The same cannot be said so easily for measures in the form of subsidies. A number of studies have looked at the impacts of subsidies in various forms of rebates and subsidized loans [2, 12, 35, 53, 57, 64, 74, 77].[4] Most find that the subsidy does have a positive effect on the choice of more efficient appliances. In general, rebates at purchase are more effective per euro compared to subsidised loans. Tax credits are also relatively cost effective when measured in terms of the cost per ton of CO_2 removed. Two main drawbacks related with rebates are free-ridership and rebound effects. Firstly, using a choice experiment in Switzerland, Banfi et al. [5] find that willingness to pay (WTP) for energy-saving measures generally exceed the cost of such measures. Grösche and Vance [40] identity this as a necessary condition for free-ridership, and find that roughly 50% of the western households in Germany also present a WTP higher than the observed cost for certain retrofit options. Secondly, Galarraga et al. [35], find a significant rebound effect from the rebates on purchase in that energy bills rise for those who purchase the more efficient appliances. On the other hand an increase in tax has no such rebound effect and a smaller welfare cost. Alberini et al. [2] find no reduction in electricity consumption for those who purchase a heat pump under a rebate but a 16 % reduction among those who made the same purchase without a rebate, suggesting that the rebound effect is greater with the subsidy.[5] Finally Markandya et al. [53] make a direct comparison between a tax incentive and a subsidy and find that the welfare cost of the subsidy is almost always higher than that of a tax and the same applies to the cost per ton of CO_2 removed.

Thus we have the situation where the more politically popular instrument (subsidies) is less cost- effective than the less popular one (taxes). Yet subsidies may be on occasions more effective than other instruments that lead to energy price increases [41]. We have already noted the arguments that taxes have negative distributional effects and, although we are inclined to the view that such effects are exaggerated, should they occur it may be necessary to introduce complementary policies that product vulnerable groups from being disproportionately affected.

Another feature of the tax/subsidy instruments for energy efficiency is the wide range of values at which they are applied across different sectors. If the aim is, for example, to reduce CO_2 emissions the tax or subsidy should be such that the implied benefit to the emitter of a ton of CO_2 is the same irrespective of which

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[4] The range of subsidies is very wide and the instrument takes many forms. It is very common for example to use renovation or 'scrappage' plans, which consists of subsidizing the substitution of inefficient products by new ones with a certain energy efficiency requirements, especially during economic recessions. However, the principal goal of these plans is frequently to activate the market and not really environmental protection [10]. Nevertheless, the use of such measures is also supported by some evidence through consumer surveys which show that the up-front investment cost is one of the main factors driving consumer decisions. This is the case with low-carbon technology vehicles in the UK [54].

[5] Research on the rebound effect arising from these subsidies is problematic. The difficulty of estimating indirect rebound effects (see the discussion above) has constrained the development of research in this area (see [14]).

sector is comes from. In practice this is far from the case. Table 2 shows the implicit cost of abatement of CO_2 for different fuels for a selection of European countries.

As Table 2 shows this is far from the case. The implied abatement cost per ton of CO_2 is very high for PV and relatively low for wind and hydro. There is thus considerable scope of increasing the efficiency of the tax structure so that cost per unit reduction in CO_2 or increase in energy efficiency is the same across different sectors.

More limited information is available on obligation systems, one of the more innovative policy instruments to promote energy efficiency. Despite the fact that they are attracting a growing interest among different governments, probably due to their social acceptability, they still have a short lifespan, which strongly limits the empirical analysis. In the case of obligation or white certificates systems, their recent introduction does not allow an ex post evaluation. Researchers have mainly tended to develop summaries and reviews of the different initiatives carried out in Europe, comparing the characteristics of each system. Mundaca and Neij [55] gather information from different sources such as official documents, or interviews with experts or regulators, to carry out a multi-criteria evaluation of the experiences in UK and Italy. The analysis indicates that both systems have achieved a high degree of success because the programs were not very ambitious. One additional problem faced by such analyses is the difficulty to identify the energy savings associated with business-as-usual.

However, given the interest the European Union has shown regarding the possibility to introduce an obligation system, there have been some simulation exercises to estimate the effects of such initiative (e.g. [27, 56]). The main results of such simulations point to the existence of an important potential to reduce energy consumption from residential and commercial sectors in the EU-15, but also inform about the necessity to carefully analyze how those savings will be distributed among Member States.

Table 2 Implicit abatement costs for different fuels in the electricity sector (€/Ton)

	Hydro	Wind	Biomass	Biogas	PV	Geo-thermal	Waste
Czech Republic	83.2	21.1	59.3	166.2	790.4	::	::
France	133.2	385.2	536.8	420.7	5381.0	::	::
Germany	67.4	77.6	228.6	::	733.8	294.5	::
Italy	149.9	142.1	224.8	::	759.5	153.8	::
Netherlands	224.9	185.4	171.0	::	890.2	::	111.3
Poland	::	::	::	::	::	::	::
Spain	124.8	129.2	219.8	::	1134.3	::	84.5
United Kingdom	131.0	145.4	129.5	127.6	416.7	::	::

Source BC3: CECILIA Project

4.3 Information Systems

Regarding energy performance certificates or labeling systems, the main limitation is the lack of complete databases containing information on household energy consumption and availability of electric stock. Since energy performance certificates have been mainly used at the residential level to distinguish buildings, appliances or vehicles, the major challenge for governments is the development of multi-year surveys that collect information about household energy consumption and energy efficiency products. Such databases would allow us to identify changes in energy consumption due to the introduction of this policy measure. Due to such limitation, analysts have focused on estimating the willingness to pay of consumers for energy efficient products. It is expected that if consumers are willing to pay more for certified products this is because they are correctly recognizing and including the information provided in such certificates among their preferences and, hence, certificates are successfully providing information.

Most of these studies focus on buildings and appliances and, depending on the source of data used for such purpose, the literature can be classified in two groups: on the one hand studies that apply the hedonic price method with real data and, on the other hand, studies that generate data using experimental techniques. The former have been applied for commercial buildings, mainly in the US and some Asian countries [11, 17, 25, 29, 30, 79] and for appliances and vehicles in Spain [34, 35]; while the later have been used for the residential sector, especially in Europe [1, 2, 5, 51, 67]. The findings of the majority of these studies find a significant positive willingness to pay for such products.

Finally, as it was mentioned in Sect. 3, there are some other informational mechanisms to reduce energy consumption in residential sector that are also gaining attention for policymakers and empirical researchers, particularly billing information and smart meters. Since individual behavior is a main determinant for the effectiveness of these instruments, and real data is missing due to a lack of experiences, experimental techniques have been the most common approach to evaluate them. In particular, there are several field experiments that estimate changes in energy consumption due to the introduction of smart meters [22, 36, 50, 75] or billing information [3, 59, 69]. It is worth mentioning a large randomized natural field experiment carried out by Allcott [3] among 600,000 households across the US which found an average 2 % reduction of energy consumption by households whose electricity bill included information about the consumption of their neighbors. Similar effects were found by Houde et al. [42] for California, with an average 5.5 % decrease in electricity consumption by households who received detailed information through an innovative web interface developed by Google.

4.4 Interactions Among Policies

The general impression one gets from the survey of the literature is that governments have been operating a significant knowledge gap in this area and have been approving many different energy policies with the objective of reducing the energy efficiency gap but without a clear idea of how well they will work. This process has created a situation where many policies simultaneously co-exist in time. For illustrative purposes, Table 3 shows the current number of energy efficiency policies in France, classified by type of measure and sector.

This creates of course a situation where there are many interactions among policies. Sometimes those interactions can be negative and lead to inefficient and unexpected results, while synergies might remain unexploited. Following Tinbergen's [76] Rule, to reach efficient solutions the number of targets should be equal to the number of policies. However, the use of more than one policy in a given area is justified in the case of market failures and equity issues, as a second best approximation [6, 61, 70].

Yet, clearly the entire current mix cannot be justified on these grounds. There is a lack of literature analyzing the interaction among general energy policies, in a context of complex regulatory saturation. As it was shown in the preceding section, the academic literature has mainly focused on estimating the results from individual national policies or simulations of certain policy proposes. But little is known about the magnitude of the multiple interactions existing among energy policies. Given their real-world relevance, authors have focused on the interactions between the EU-ETS and renewable energy policies (see, for instance, [70]). However, interactions between energy efficiency and other renewable/environmental policy instruments have received less attention. Some authors point out important

Table 3 Current number of energy efficiency policies in France

Country/measures	Household	Tertiary	Industry	Transport	Cross-cutting
Financial	10	4	3	2	–
Fiscal/tariffs	4	–	–	4	–
Information/education/training	5	3	2	4	–
Legislative/info	6	3	–	1	–
Legislative/normative	7	8	1	4	–
Unknown	7	1	1	3	–
Co-operative	2	2	3	4	–
Infrastructure	–	–	–	4	–
Social planning organization	–	–	–	2	–
Other	–	–	–	–	20

Source Project ODYSSEE-MURE

interactions when green certificates and white certificates or obligation systems are introduced [16, 62, 66]. Other interactions include:

a. Increased risk for agents when reacting to one instrument or deciding on actions in the energy area to know how the other instruments will unfold over time.
b. Rebound effects from subsidies increasing energy demand across related sectors when instruments have been introduced to specifically reduce demand in those sectors.
c. The very low price in the ETS resulting in a major reduction in emissions allowances in the future so as to raise the price but, at the same time, with little knowledge on how the subsidy schemes will change in the future and what innovations they will generate.

5 Conclusions

Improving energy efficiency has become one of the preferred options for governments to reduce energy consumption and its associated costs and emissions. In this chapter we look at the different polices and present the general context for public intervention in this area. Experts have identified a large number of measures that promote energy efficiency. Unfortunately many of them are not cost effective. This is a fundamental requirement for energy efficiency investment from an economic perspective. However, the calculation of such cost effectiveness is not easy: it is not simply a case of looking at private costs and comparing them to the reductions achieved. There are significant externalities to take into account and there are also macroeconomic effects. For instance, at the aggregate level, improving the level of national energy efficiency has positive effects on macroeconomic issues such as energy dependence, climate change, health, national competitiveness and reducing fuel poverty. And this has direct repercussions at the individual level: households can reduce the cost of electricity and gas bills, and improve their health and comfort, while companies can increase their competitiveness and their productivity. Finally, the market for energy efficiency could contribute to the economy through job and firms creation.

Despite all these benefits, the market for energy efficiency presents several market failures and other market barriers that make the level of private investment suboptimal. Incomplete information, the principal-agent problem, the difficultness to access to capital, bounded rationality or risk aversion, are among the important hurdles. This situation not only justifies public intervention, but also determines the context for such intervention. Due to the multitude of market imperfections, no single policy is sufficient to promote energy efficiency alone. As a result, during the last decades governments have been implementing codes and standards to guarantee a minimum level of energy performance, economic instruments to give incentives for reducing energy consumption, and more recently new market-based instruments such as permits, obligations or energy performance certificates.

The current situation is thus characterized by a simultaneous co-existence of a multitude of policies, which can be confusing and inefficient due to their negative interactions.

The academic literature has focused on estimating the individual results of each public initiative. Different approaches have been adopted for such evaluation; however little is known about the potential interactions among policies. In a multi-policy context there is a large probability for negative interactions and unexploited synergies among policies. This should be the area for future academic work, and the corresponding findings should be used to design and implement policy packages (see e.g. [32]).

Given the range of instruments that exist it is not easy to select the optimal combination. There is a need to carry out a comprehensive review of all instruments in an economy-wide framework so interactions can be specifically allowed. The aim for a transition to reform policies in this sector should be based on:

- Eliminating those policies that do not work cost effectively in the sector and for the purposes for which they were intended.
- Setting the levels of the others so that they take account of cross and interaction effects.
- Bringing in additional instruments that address problems created by the ones that have been introduced (e.g. distributional issues arising from energy taxes).

This transition cannot be made overnight but it is time to make a start and hopefully over the next decade we will have a more effective policy framework to promote energy efficiency. A key role in this will have to be played by the economic analysis of the cost effectiveness of different instruments within an agent-based framework.

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Understanding the Link Between Aggregated Industrial Production and the Carbon Price

Julien Chevallier

Abstract This chapter assesses the extent to which economic activity and the carbon price are linked. Carbon price drivers can be mainly related to energy and institutional variables. However, the influence of the macroeconomic environment shall not be undermined. Various approaches exist in the literature, which favor financial market variables over macroeconomic variables. Following a review of the state of the EU ETS, the main channel of transmission between the variation of macroeconomic activity and the carbon price is recalled, by using the aggregated industrial production as a proxy. An original empirical application unfolds, by studying the carbon-macroeconomy relationship in the threshold VAR model during 2005–2013. Further research is called upon in nonlinear econometrics.

Keywords Carbon price · Economic activity · Industrial production · Nonlinear time series

JEL Codes Q40 · Q48 · Q54

1 Introduction

The EU Emissions Trading Scheme (EU ETS) is arguably the flagship of Europe's climate policy approach to achieve its 2020 emissions target (−20 %). As a cap-and-trade program, it represents a central economic tool to achieve a cost effective and smooth transition to a low carbon economy. However, while carbon markets have been the predominant policy response to address greenhouse gases mitigation in many countries, the carbon economy currently looks bleak. There are currently no binding global targets beyond 2012 (post-Kyoto). In December 2011, the

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Durban COP/MOP meeting has given a temporary lifeline to the CDM, but not on its longer term future (after 2015).

As a consequence, the uncertainty about the future of the markets, in combination with recurrent fears about "over-allocation" within the EU ETS as well as the impact of the recession on emissions themselves, have kept carbon prices at relatively low levels. Despite this absence of a binding international agreement, several new or emerging systems and regional initiatives are underway that result in the creation of new domestic markets (RGGI, California, Western Climate Initiative, Australia, China, South Korea, REDD+ , etc.).

Against this institutional background, economic activity is perhaps the most obvious and least understood driver of CO_2 price changes. Economic growth leads to increased energy demand and higher industrial production in general. Despite numerous contributions in the field of carbon price modeling (e.g., supply and demand fundamentals, and expected future regulatory action), the last puzzle to be solved in relation to the price drivers of European Union Allowances (EUAs) is thus to determine the influence of economic activity, through changes in CO_2 emissions levels.

This link between the carbon market and economic activity can be captured by the interaction between the price of CO_2 and changes in the levels of industrial production. Indeed, it is widely acknowledged in macroeconomics that changes in the rate of utilization of industrial capacities provide an early warning of future changes in the levels of GDP. Therefore, industrial production can be considered as a good proxy for the evolution of the economic activity in the industrial sectors regulated by the EU ETS.

This relationship may be understood intuitively: as industrial production increases, associated CO_2 emissions increase, and therefore more CO_2 allowances are needed by operators to cover their emissions. This economic logic results in carbon price increases *ceteris paribus*. More work is needed on this topic, especially to understand the adjustment process of carbon prices to the macroeconomic environment, for instance by focusing on the underlying nonlinearities of the data. Since 2008, the deep recession arising from the financial crisis has spread to the sphere of commodities (including CO_2), and it has very much depressed the carbon price signal. As of today's state-of-the-art literature, there lacks a comprehensive study on the adjustment of the price of carbon to the global economic recession that this chapter aims to fill.

The remainder of the chapter is organized as follows. Section 2 provides a background discussion on the current status of the EU ETS. Section 3 explains the main mechanism at stake concerning the link between the carbon price and the macroeconomy, along with the findings from previous literature. Section 4 develops the empirical analysis based on the class of threshold VAR models. Section 5 briefly concludes.

2 Current Issues in the EU ETS

As a brief reminder, the perimeter of the scheme covers approximately 11,000 installations in the EU27, i.e., it accounts for 45 % of EU greenhouse gases.

In addition, the ETS is a liquid market, with millions of allowances traded each day on a number of exchanges, and over-the-counter. For instance, the average daily trading volume in 2011 was equal to 23 million EUAs (including futures), summing up to an amount of 6 billion annual trading volume. Until the end of June 2012, the accumulated total trading of futures since the creation of the scheme was equal to 20.4 billion allowances.

In this section, we first discuss the figures of the 2011–2012 compliance data, and second some uncertainties pertaining to the future development of the European carbon market.

2.1 A Look at the 2011–2012 Compliance Data

According to the compilation of preliminary data by Point Carbon,[1] the phase II of the EU ETS was oversupplied by 1.7 billion CO_2 units, with almost half the surplus coming in 2012. Let us breakdown this information over the last two compliance years 2011–2012.

2.1.1 Year 2011

According to Carbon Market Data,[2] installations were long by 87 Mt in 2011. It implies that installations emitted in total 4.9 % less CO_2 than the number of allowances allocated—a total of 1,985 million allowances. Similarly, a 2.1 % drop in CO_2 emissions was recorded during the corresponding year.

In 2011, emissions from the combustion sector (which accounts for 70 % of EU ETS emissions) showed a 2.2 % decrease. Other industrial sectors have seen their CO_2 emissions falling for ceramics (−32.3 %), cement (−20.2 %), or steel (−14.1 %) for instance.

Following the release of verified emissions reports[3] for the year 2011, RWE, Vattenfall and E.ON were the three biggest CO_2 emitters of the EU ETS by emitting

1 See the news release " *EU carbon market oversupplied by 1.7 bln: analysts*" dated April 2, 2013 at www.pointcarbon.com

2 Available at www.carbonmarketdata.com. Last accessed October 4, 2012.

3 These figures are calculated at group level, taking into account both minority and majority stakeholdings in other companies included in the EU emissions trading scheme. Figures do not include the EU allowances distributed for free to new entrants, as these data are not shown in the Community Independent Transaction Log (the EU carbon trading registry, also called CITL). A "*new entrant*" is defined in the EU directive establishing the carbon trading scheme as a new

respectively 141 $MtCO_2$, 92 $MtCO_2$ and 86 $MtCO_2$. The Italian energy giant Enel is ranked at the fourth position, with CO_2 emissions totaling 78 $MtCO_2$. Finally, EDF, the French group, was in 2011 the fifth biggest emitter with 67 $MtCO_2$.

Additional data are available for the year 2011:

- The three companies with the *highest surplus* of freely allocated EUAs were two steel makers and one cement manufacturer: ArcelorMittal (34 Mt), Corus (16 Mt) and Lafarge (11 Mt). This ranking is unchanged compared to the previous year.
- The three companies having in 2011 the *highest shortage* of EU carbon allowances are all involved in the electricity generation business.[4] These companies are RWE (shortage of 49 Mt), Vattenfall (27 Mt) and Drax Power (12 Mt).
- The three companies having surrendered the biggest number of *Certified Emissions Reductions* (CERs) to EU Member States are ArcelorMittal (25 million CERs), Lafarge (11 million CERs) and Enel (7.5 million CERs).
- The three companies having surrendered the biggest quantity of *Emissions Reductions Units* (ERUs) for 2011 compliance are ThyssenKrupp (8.2 million ERUs), ArcelorMittal (4 million ERUs) and Repsol (3.5 million ERUs).

Table 1 displays the company rankings of the five biggest CO_2 emitters per country (the United Kingdom, Germany, France, Italy and Spain), taking into account power plants and factories based on the respective national territory (i.e. this is not an EU-wide company ranking).

These figures are characteristic of a wider macroeconomic context of fall in demand (allowances and energy), mostly due to the economic downturn and mild temperatures during the reference compliance year.

Note that this diagnostic does not apply uniformly to all EU ETS sectors. For instance, an increase in CO_2 emissions was recorded in the glass sector (+3 %).

2.1.2 Year 2012

In 2012, installations were long by 164 Mt in 2012 (they emitted 164 million tons CO_2 less than their number of freely received carbon allowances).[5] This figure is derived from the verified emissions data for 95 % (in volume) of the 11,300 installations included in the trading scheme. It shows that EU ETS installations

(Footnote 3 continued)
installation, or as an existing installation that has experienced a change of its activity "*in the nature or functioning or extension of the installation*". Data on the number of EU carbon allowances distributed to these new entrants are not made available publicly in the EU carbon registry. Only the emissions reports of these installations are published.

[4] These three companies all have an energy mix with a high proportion of coal- or lignite-fired electricity generation.

[5] These figures include the 27 EU countries except Bulgaria and Cyprus.

Table 1 Company rankings of largest emitters in 2011 by Country *Source*: Carbon market data

	Company	Sector	CO_2 Emissions 2011 ($MtCO_2$)	Free carbon allowances 2011 ($MtCO_2$)
UK				
1	EDF	Power and heat	22.4	16.0
2	Scottish and Southern Energy	Power and heat	22.1	15.3
3	Drax Power	Power and heat	21.5	9.5
4	E.ON	Power and heat	19.0	17.6
5	RWE	Power and heat	15.7	17.0
Germany				
1	RWE	Power and heat	114.3	62.3
2	Vattenfall	Power and heat	72.9	48.8
3	E.ON	Power and heat	42.4	32.8
4	Evonik Industries	Chemicals	20.4	20.2
5	ThyssenKrupp	Iron and steel	17.6	25.6
France				
1	ArcelorMittal	Iron and steel	18.8	24.5
2	EDF	Power and heat	15.7	19.2
3	Total	Oil and gas	10.4	13.1
4	GDF SUEZ	Power and heat	6.3	8.9
5	Lafarge	Cement and lime	4.6	6.0
Italy				
1	Enel	Power and heat	36.8	32.2
2	Eni	Oil and gas	24.0	25.5
3	Edison	Power and heat	19.7	17.3
4	Riva Group	Iron and steel	10.4	13.8
5	E.ON	Power and heat	7.6	8.1
Spain				
1	Endesa (Enel)	Power and heat	34.5	23.4
2	Repsol	Oil and gas	14.2	16.0
3	Gas Natural Fenosa	Power and heat	14.2	11.9
4	hc energía (EDP)	Power and heat	8.3	5.3
5	Iberdrola	Power and heat	7.3	8.3

emitted—in total—8 % less CO_2 than the number of allowances they received for free.

EU countries allocated to their installations a total of 2,034 million allowances. Verified emissions data submitted so far show that these installations emitted during the same period 1,786 Mt CO_2. This represents an average decrease in CO_2 emissions of 1.4 % per installation in 2012 over 2011 (this figure takes into account only the installations that have submitted their emissions report).

This decrease in CO_2 emissions was expected by most analysts, and may be due to the economic stagnation in Europe combined with the effect of energy efficiency and renewable energy policies, despite low coal and carbon prices.

RWE, Vattenfall and E.ON were the three biggest CO_2 emitters of the EU emissions trading scheme during the year 2012. RWE, E.ON and Vattenfall emitted in 2012 respectively 157 $MtCO_2$, 92 MtCO2 and 90 MtCO2. RWE had in 2012 a shortage of 45 million carbon allowances.

Additional data are available for the year 2012:

- The three companies with the *highest surplus* of EUAs were two steel makers and one cement manufacturer: ArcelorMittal (37 million EUAs surplus), Tata Steel (17 million EUAs surplus) and Lafarge (12 million EUAs surplus).
- The three companies having in 2012 the *highest shortage* of EU carbon allowances are all involved in the electricity generation business. These companies are RWE (shortage of 45 Mt), Vattenfall (28 Mt) and Enel (17 Mt).
- The three companies having surrendered the biggest number of *CERs* to EU Member States are E.ON (27 million CERs), Enel (16.5 million CERs) and GDF-Suez (8.5 million CERs).
- The three companies having surrendered the biggest quantity of *ERUs* for 2012 compliance are RWE (15 million ERUs), CEZ (12.5 million ERUs) and E.ON (11 million ERUs).

In 2012, only two countries allocated to their installations—in aggregate - less free allowances than they emitted: Germany (29 Mt) and the United Kingdom (2.5 Mt). All the other countries allocated to their installations more allowances than the amount of carbon emitted in 2012. Romania (−26 Mt), France (−25 Mt), the Czech Republic (−17 Mt), Spain (−17 Mt), and Poland (−16 Mt) are topping the list of countries with a surplus in EU carbon allowances.

In terms of emissions evolution between 2012 and 2011, nine countries saw an increase of their CO_2 emissions. Malta (+7.5 %), Ireland (+7 %) and the UK (+4.7 %) experienced the highest increases in CO_2 emissions. Countries that witnessed a decrease in their CO_2 emissions level in 2012 are topped by Northern European countries: Finland (−15 %), Denmark (−15 %), Estonia (−8.5 %) and Sweden (−8.3 %). Finland and Denmark had made exactly the same performance last year, i.e., these two countries reduced their CO_2 emissions by nearly 30 % from 2010 to 2012.

Figure 1 shows the emissions-to-cap ratio in 2012 by country. This graph reveals that only two countries (Germany and the UK) were short of allowances during the compliance year 2012, while other countries were in a more favorable position, with larger amounts of allocated allowances than verified emissions for that vintage.

Following this up-to-date presentation of the state of the EU ETS in terms of emissions data, we address in the next section various regulatory issues regarding the evolution of the scheme.

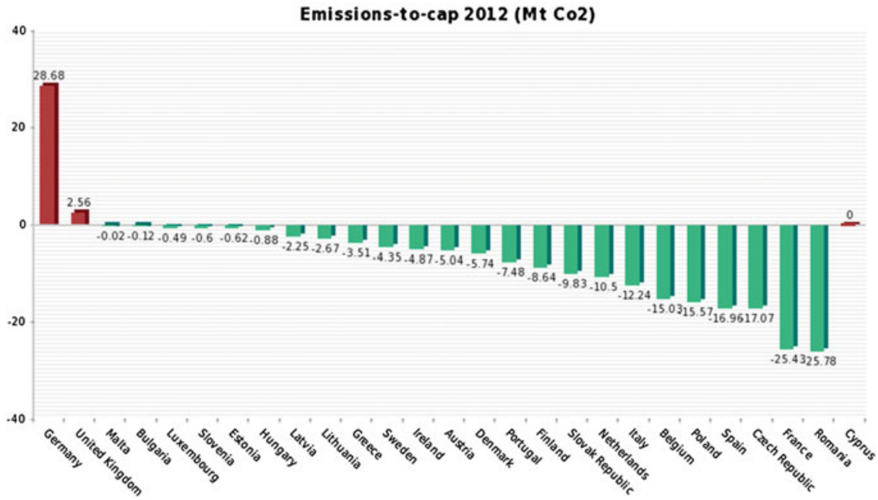

Fig. 1 Emissions-to-cap ratio in 2012 by country *Source* Carbon market data

2.2 *Rising Uncertainties*

First, uncertainties are especially acute on the supply side of the market. The cumulative surplus transferable into phase III has reached 1.5 Gt CO_2-equivalent (or 80 % of annual emissions of the EU ETS installations). The current low price of EUAs (in the range of 6–7 Euro/ton of CO_2) logically responds to this imbalance between the supply and demand of allowances.

Given the current economic outlook, which options are available to the regulator to attempt to fix the situation? One solution could lie in the permanent cancellation of the quota set-aside, which would have the direct effect to restore the balance between supply and demand, and hence increase the price of carbon.

In December 2011, the EP ENVI has voted on the perception that a 1.4 billion permanent set-aside was decided. Further on this topic, the European Commission published in November 2012 its ETS market review, as part of plans to tackle a huge surplus of carbon permits that has depressed the market.[6]

Besides, the proposal to delay the CO_2 allowance auctions (backloading) was rejected by the European Parliament on April 16, 2013 and referred to the Parliament's ENVI Commission. A new plenary session vote has been scheduled for early July 2013. This state of affairs has led some critics to consider the EU ETS as a "zombie" public policy (Tendances Carbone [28] characterized by a four euro price path.

Second, the scope of the EU ETS has recently been extended. Since January 1, 2012 the aviation sector has been included in the EU ETS—thereby tackling the

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[6] See the Point Carbon news article at http://www.pointcarbon.com/news/1.1999756. Last accessed October 4, 2012.

CO_2 emissions coming from transport. However, lawsuits have been coming from some EU as well as non-EU Member-States to protest against this scheme. Against the over-allocation background for other (non-aviation) EU ETS sectors, we may wonder whether this extension to aviation was such as good idea, and whether the timing for such a bold regulatory move was appropriate.

The legal challenge to the validity of the EU ETS, as applied to aviation and which was instigated by the Air Transport Association of America, supported by the International Air Transport Association (IATA) and the National Airlines Council of Canada (NACC), finally concluded with the judgment of the European Court of Justice Grand Chamber published on December 21, 2011. Not unexpectedly, the ECJ confirmed the validity of the EU ETS.[7] During the lawsuit, complex questions arised as to the potentially extra-territorial nature of the ETS as applied to airlines, whether it infringes sovereignty of airspace of non-EU countries, and whether the EU ETS involves an unlawful charge or a tax on fuel [20].

Although the aviation component of the EU ETS has survived, the ECJ case by no means brings to an end the legal and political disputes on this issue. Airlines continue actively to consider their options for further legal action within the EU; a dispute resolution process under the aegis of ICAO (the International Civil Aviation Organization) continues to be a likely forum for further challenge; the US is pursuing its own legislation, which would prohibit US carriers from complying with the EU ETS, and certain international carriers and industry associations are threatening straightforward noncompliance.

As a consequence, Point Carbon[8] indicates that political pressure may force the EU to show flexibility when it comes to resolving the dispute over including airlines in its carbon market - by either being lenient when it comes to policing the scheme or generously interpreting conditions that allow it to repeal the law.

Last but not the least, as mentioned in the Introduction, the status of the CDM and further EU ETS linkage are undermined by the absence of post-Kyoto agreements (after December 2012). Taken together, all these facts contribute to cast a veil of uncertainty on the future development of world and regional carbon markets.

3 The Link Between the CO_2 Price and Industrial Production

In this section, we recall first the economic mechanism by which CO_2 emissions, industrial production and carbon prices are theoretically connected. Then, we provide an overview of the current literature on this topic.

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[7] Air Transport Association of America e.a., v Secretary of State for Energy and Climate Change, Case C-366/10.

[8] Available at http://www.pointcarbon.com/news/1.2004752. Last accessed on October 4, 2012.

3.1 Mechanism

What is the impact of economic activity on the growth rate of carbon prices from an empirical point of view? Absent energy efficiency improvements (at least in the short-term), the link between growth and carbon pricing unfolds as follows:

1. Economic activity fosters high demand for industrial production goods.
2. In turn, companies falling under the regulation of the EU ETS need to produce more, and emit more CO_2 emissions in order to meet consumers' demand.
3. This yields to a greater demand for CO_2 allowances to cover industrial emissions, and ultimately to carbon price increases.

Of course, it would be better to work directly with CO_2 emissions at the installation level, but there is a high degree of complexity in accessing this data, and making it available to the econometrician. Hence, we choose to proceed with the industrial production index as a good proxy of economic activity in this chapter.

3.2 Previous Studies

Among early studies, we may refer to the theoretical literature reviews by [13, 27], who identified the following drivers of CO_2 allowance prices:

- *Policy and regulatory issues of the EU ETS*: these include National Allocation Plans (NAPs), auctioning share of allowances, banking and borrowing allowances possibilities, new entrants reserve, new covered sectors, etc.;
- *Emissions levels*: among the factors impacting CO_2 emissions, we may distinguish between

    1. Economic activity: industrial production by covered installation, electricity power demand by others sectors;
    2. Energy prices: Brent, natural gas, coal;
    3. Weather conditions: temperature and rainfalls.

Therefore, we observe that economic activity was directly thought as being one of the fundamental drivers of carbon prices in the literature that was published before the creation of the EU ETS.

However, the first empirical studies neglected that impact, and focused more heavily on the role played by other energy markets in shaping the price of carbon. We may cite in this strand of literature the papers by:

- Kanen [22]: the author finds that coal, natural gas and oil prices impacted carbon futures of maturity December 2006;
- Mansanet et al. [25]: they document that Brent ICE and natural gas NBP impacted carbon spot prices from January to November 2005;

- Bunn and Fezzi [6]: in a cointegrated vector error-correction model, the authors establish that natural gas and carbon prices jointly influence the equilibrium of electricity.

Interestingly, one has to wait until late 2008–2009 to find published research papers including explicitly industrial production (as a proxy of economic activity) as one additional factor potentially impacting the price path of carbon. These first stylized analyses are due to [2, 3], who provide the first rigorous econometric exercises aimed at disentangling the potential impacts ranging from production to environmental conditions on carbon prices. By instrumenting industrial production indices at the EU ETS sector-level, the authors show empirically that fluctuations in the level of economic activity are a key determinant of the level of carbon price returns in the combustion, paper and iron sectors (which account for nearly eighty percent of allowances allocated), and in four countries (Germany, Spain, Poland, UK). Although, one limit of these studies is that they considered exclusively linear econometric models, while the underlying relationships at stake could essentially be understood as being nonlinear (for instance, the effects of temperatures on carbon prices can only be detected above or below a given threshold). This limitation has now been tackled by some of the papers mentioned below.

In a different setting, Hintermann [21] derives a structural model of the allowance price under the assumption of efficient markets during phase I of the EU ETS. In his model, changes in the optimal amount of abatement are a function of several variables including temperatures, precipitations, fuel prices, but also a proxy for overall economic performance in the EU: the FTSE Eurotop 100. This latter variable is a tradable index representing the 100 most highly capitalized blue chip companies in Europe, and therefore belongs to the category of financial markets indicators.

It is worth noting here that the econometrician has broadly two types of choices when deciding on the proxy for economic activity. Either he can specify a variable, which is by definition macroeconomic, in the sense that it corresponds to the reality of physical exchanges in the economy (such as industrial production processes), or he can opt for a more financial approach, whereby liquid and efficient markets are supposed to reflect instantly the public information readily available concerning the state of the economy (e.g., news releases on macroeconomic aggregates).

Depending on this choice, different types of conclusion will of course be drawn from the study. For a genuine macroeconomic approach, industrial production-type indices will certainly be the preferred choice of the econometrician. As another consequence, the following literature can be further divided into two subcategories:

1. **The “financial markets” approach**: these studies include not only Hintermann [21], but also Creti et al. [14] who use the Dow Jones Euro Stoxx 50 as the equity price index in their estimation strategy of carbon price drivers (including as well Brent and the switch price). Aatola [1] use the FTSE 350 as their economic activity proxy, among other energy market fundamentals.

Note that the investigation of macroeconomic risk factors[9] specific to the EU ETS by [7], as well as the impulse response function analysis in the Factor-Augmented Vector AutoRegressive (FAVAR) framework conducted by [8] could also fall in this category.

2. **The "macroeconomic" approach**: in this category, we will find the early work by [2, 3], as well as a series of new studies.

First, Chevallier [9] provides several nonlinearity tests for the univariate time series of industrial production and carbon prices, which can satisfactorily be fitted with Self-Exciting Threshold AutoRegressive (SETAR) models. In addition, a multivariate econometric strategy featuring industrial production as the logistic transition function in a Smooth Transition AutoRegressive (STAR) model including both variables brings fruitful results. On the one hand, contemporaneous changes in the industrial production index impact negatively carbon price changes (i.e., the decrease in industrial production precedes the decrease in carbon prices). On the other hand, changes in the industrial production index lagged one period impact positively carbon price changes (i.e., the uptake in economic activity encourages the carbon price to go up).

Second, Chevallier [10] uses again the EU 27 industrial production index computed by Eurostat as a proxy of economic activity in the perimeter of EU ETS sectors. This choice is assessed based on a preliminary forecasting exercise including various candidates (monetary, industrial, and financial variables): it could be shown that the industrial production index minimizes all criteria. Then, the originality of the article lies in the two-regime threshold cointegration exercise between EU industrial production and the carbon price. The threshold Vector Error-Correction Model (VECM) estimates reveal that the EU industrial production index impacts positively the EUA futures price: the carbon-macroeconomy relationship goes from the EU industrial production index (lagged one period) to the carbon futures price. On the contrary, the EUA futures price has no statistically significant effect on the EU industrial production index. In short, the industrial production index governs most of the adjustment from the short-run to the long-run equilibrium of the model. Should any short-term deviations occur, the industrial production index acts as a feedback force to restore the long-run equilibrium relationship. Hence, it can be concluded that industrial production leads the nonlinear mean-reverting behavior of the carbon price, but not vice versa.

Third, Chevallier [11] confirms that the presence of nonlinearities may contribute to explain why early regression studies did not capture well the carbon-macroeconomy relationship. In a two-regime Markov-switching model between industrial production and carbon prices, the author shows that industrial production has two types of effects on the carbon price: positive during the expansion regime, and negative during the recession regime. Macroeconomic activity is likely to affect

[9] i.e., dividend yields, junk bond yields, T-bill rates and market portfolio excess returns in the Fama-French literature.

carbon prices with a lag, due to the specific institutional constraints of this environmental market. Besides, the Markov regime-switching model captures most of the shocks identified on the carbon market (January-April 2005, April-June 2006, October 2008, and April 2009-present). In line with previous studies, no statistically significant impact going from the carbon price to industrial production could be detected (i.e., there is no "bounce back" effect). The results are robust to the introduction of energy dynamics (e.g., Brent, gas, coal).

While there seems to remain considerable uncertainties regarding the evolution of this carbon-macroeconomy relationship in phase III of the EU ETS with the shift to auctioning and the need to meet the EC 20/20/20 targets, the bottom line of this work can be summarized as follows. The carbon-macroeconomy relationship seems adequately captured by two-regime threshold error-correction and two-regime Markov-switching VAR models compared to linear models as main competitors.

Finally, "**mixed equity/industrial production**" **econometric strategies** can also be found:

- Bredin and Muckley [5] have used the industrial production index computed by Eurostat to capture the influence of economic activity in their equilibrium model of phase II carbon prices (including as well energy prices, equity prices and temperatures deviations). The financial markets indicator used is the Eurex Dow Jones Euro Stoxx futures contract. According to the authors, the motivation for including this variable is that it offers an up-to-date indicator of expectations on both financial and economic conditions at the required daily frequency. Further, given the financial nature of the underlying asset, they consider including such a proxy informative. We can certainly agree upon that statement concerning the benefits of a mixed financial/macro approach.
- Mansanet-Bataller [24] have used the industrial production index calculated by *Tendances Carbone*, in conjunction with financial indicators such as the EU Economic Sentiment Index, the slope of the Euro area yield curve, the Reuters momentum variable concerning the EUA market, and the CBOE VIX volatility indicator. During phase II of the EU ETS, statistical significance could only be found for the EUA momentum variable.

Table 2 provides a useful summary of the categories of indicators used in previous studies as proxy for economic activity:

4 Empirical Analysis

In our empirical analysis, we wish to develop a Threshold VAR model (TVAR) applied to the carbon-macroeconomy relationship. The focus here is to study the inter-relationships between the EU 27 industrial production index and the price of CO_2 in a nonlinear framework.

The necessity to adopt such a methodological viewpoint compared to early studies—which were essentially based on linear regressions—has been further

Table 2 Summary of previous studies indicators of economic activity for carbon markets

Reference	Period	Economic activity proxy	
		Financial approach	Macroeconomic approach
Aatola et al. [1]	January 2005–December 2010	FTSE 350	
Alberola et al. [2]	July 2005–April 2007		*Tendances Carbones* EU ETS sectors industrial production
Alberola et al. [3]	July 2005–April 2007		*Tendances Carbones* EU ETS sectors industrial production
Chevallier [7]	April 2005–October 2008	Euronext 100	
Hintermann [21]	January 2005–June 2007	FTSE Eurotop 100	
Bredin and Muckley [5]	July 2005–December 2009	Eurex Dow Jones Euro Stoxx	Eurostat EU 27 industrial production index
Chevallier [8]	April 2008–January 2010	Broad dataset of financial times series	Broad dataset of macroeconomic time series
Chevallier [9]	January 2005–July 2010		EU 27 Eurostat industrial production index
Chevallier [10]	January 2005–July 2010		EU 27 Eurostat industrial production index
Chevallier [11]	January 2005–July 2010		EU 27 Eurostat industrial production index
Creti et al. [14]	June 2005–December 2010	Dow Jones Euro Stoxx 50	
Mansanet-Bataller et al. [24]	March 2007–March 2009	EU Economic Sentiment Index, Euro area yield curve, Reuters EUA momentum, CBOE VIX	*Tendances Carbone* industrial production index

documented by [12]. In his review of the main results of the CO_2 allowances price drivers, the author shows indeed that the results that were previously established can further vary depending upon the specification of higher or lower regimes in the time series data.

In what follows, we aim at taking the current literature on the carbon-macroeconomy relationship one step further by analyzing this link in the TVAR framework. This econometric strategy will allow us to decompose the joint variation of carbon prices and industrial production in two (high and low) regimes.

As such, it provides a useful and updated extension of the studies by Chevallier [9], SETAR and STAR models), Chevallier [10], two-regime Threshold cointegration), and Chevallier [11], two-regime Markov-switching VAR model).

4.1 Data

Let us first present the data used in this study. The dataset contains CO_2 futures prices and the EU 27 Industrial production index, which were obtained from the European Climate Exchange (ECX), Thomson Financial Datastream, and Eurostat. The data sample goes from the opening of ECX on April 22, 2005 to January 25, 2013 (i.e. a sample of 2,008 *daily* observations).

The carbon price is the ECX EUA Futures price series in EUR/ton of CO_2, rolled-over using front months contracts. In addition, concerning the macroeconomic variable of interest, we follow thoroughly the approach by [10], who selected the EU 27 Industrial Production Index by Eurostat as the variable of interest to be used as a proxy for the influence of economic activity (to cope with the limitation of being unable to observe actual CO_2 emissions at the plant level).[10]

Both series are pictured in Fig. 2. Concerning the EU industrial production (on the right Y-axis), we may distinguish three distinct phases during our study period. First, the period going from January 2005 to May 2008 may be viewed as a phase of economic growth. Second, we notice after May 2008 an abrupt decline in the industrial production, characterizing the entry of EU economies into the recession. These events follow with some delay the developments of the US economy, following the first interest rate cut by the Federal Reserve in July 2007. This event is mostly viewed as the start of the economic downturn, as the first signs of financial distress in the housing sector met the headlines. Third, from April 2009 until July 2010, we may observe a timid uptake in the industrial production. Therefore, our study period contains an interesting mix of economic growth, recession and recovery that we aim at analyzing jointly with the behavior of EUA Futures prices (on the left Y-axis). The latter time series seems to follow the same pattern, with the presence of shocks during 2005–2007 originating from institutional features of the EU ETS (see [16] for an exhaustive coverage of this topic).

Descriptive statistics are presented in Table 3. They provide useful information on the distributional characteristics of the time series considered, and more especially

[10] The EU 27 industrial production index has a base 100 in 2000, and is seasonally adjusted. The index is converted from monthly to daily frequency by using the Matlab function by L. Shure, which performs linear interpolation so that the mean square error between the original data and their ideal values is minimized.

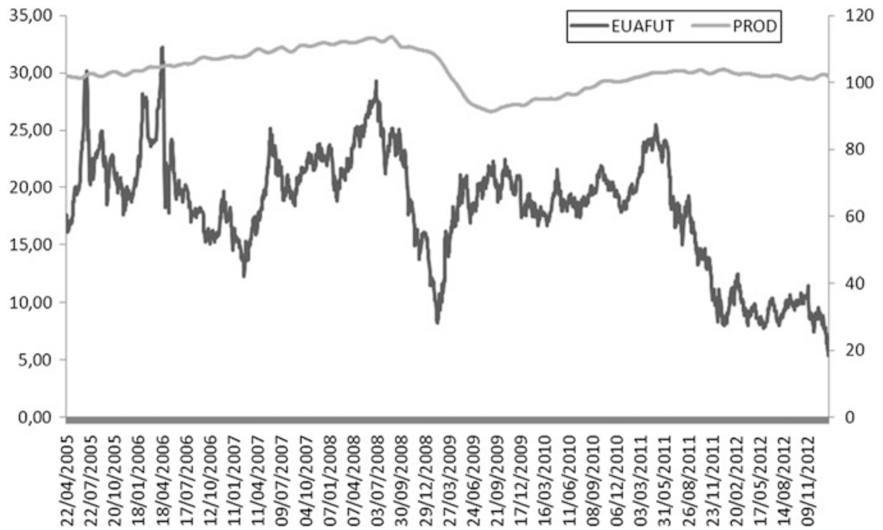

Fig. 2 ECX futures price and EU industrial production index *Source*: European climate exchange, Thomson financial datastream, Eurostat

Table 3 Summary statistics for CO_2 and macroeconomic variables

	D(EUAFUT)	D(PRODIND)
Mean	−0.000573	−8.58E-07
Maximum	0.269001	0.000980
Minimum	−0.288246	−0.001910
Standard deviation	0.030103	0.000515
Skewness	−0.191137	−1.169207
Kurtosis	13.66459	5.358974
JB	9527.929	923.0890
Prob(JB)	0.000000	0.000000
Obs.	2008	2008

Note EUAFUT stands for the ECX EUA Futures price, and PRODIND for the EU 27 Industrial Production Index from Eurostat. The operator D(.) refers to the log-return transformation of the time series. Std. Dev. Stands for Standard Deviation, JB for the Jarque Bera Test Statistic, Prob (JB) for the critical value of the Jarque Bera Test Statistic, and Obs. for the number of observations in *daily* frequency

concerning their non-Gaussianity. The price series are not stationary when taken in raw form, and stationary when transformed to log-returns (i.e., $I(1)$). Usual unit root tests (ADF, PP, KPSS) are not reproduced here to conserve space.

4.2 TVAR Model

Next, we present formally the TVAR model used. We build here on [4]'s notations:

$$X_t = A^0(L)X_{t-1} + [A^1(L)X_{t-1}]I(c_{t-d} > r) + \varepsilon_t \tag{1}$$

where X_t denotes a vector a time series, $A^0(L)$ and $A^1(L)$ are lag polynomials, and ε_t is the error term. c_{t-d} is the threshold variable that determines which regime the system is in, r is the threshold critical value, $I(c_{t-d} > r)$ is an indicator function that equals 1 when $c_{t-d} > r$, and zero otherwise. The threshold value r is not known a priori, and must be estimated (see [18]).

Before estimating the TVAR model, we need to implement a nonlinearity test in order to test formally whether the threshold-type behavior is rejected, or not. The test is the multivariate extension by Hansen [19, 23] of linearity test against various thresholds. As in the univariate case, the first threshold parameter is estimated by Conditional Least Squares (CLS) upon a grid of potential values for the threshold and the delays. Then, for the second threshold, a conditional search with one iteration is performed. Instead of a *F*-test comparing the Sum of Squared Residuals (SSR) for the univariate case, a Likelihood Ratio (LR) test comparing the covariance matrix of each model is computed:

$$LR_{ij} = T(\ln(\det \hat{\Sigma}_i) - (\ln(\det \hat{\Sigma}_j)) \tag{2}$$

with $\hat{\Sigma}_i$ the estimated covariance matrix of the model with *i*-regimes (and *i*-thresholds), *det* the notation for the determinant of the matrix, and T the number of observations. Three tests are presented:

1. Test 1 versus 2: Linear VAR versus 1-threshold TVAR;
2. Test 1 versus 3: Linear VAR versus 2-threshold TVAR;
3. Test 2 versus 3: 1-threshold TVAR versus 2-threshold TVAR.

The goal is to determine first whether a purely linear model is rejected (in favor of one or two thresholds). In the second step, once the presence of the threshold(s) has been confirmed, we aim at identifying whether a model with one or two thresholds is preferable (see [29] for more details).

The model hyper-parameters (i.e. the possible thresholds and delays value) are determined by running an automatic search upon a grid of potential values[11] (for more details, see [23]). For a fixed threshold variable, the model is linear, so that the estimation of the two higher- and lower-regimes can be done directly by CLS. The standard errors coefficients provided for this model are taken from the linear regression theory, and are to be considered asymptotical [17, 30].

[11] An exhaustive search is conducted over all the possible combinations of values of the specified hyper-parameters. These results are not shown here to conserve space, and may be obtained upon request to the author.

Table 4 TVAR model for EUAs and EU industrial production

Diagnostic tests	Statistics	*p*-value
LR Test of linearity (1 versus 2)	39.2378	0.0000
LR Test of linearity (1 versus 3)	77.3049	0.0000
LR Test of TVAR(1) against TVAR(2) (2 versus 3)	38.0671	0.0000
Best unique threshold (Delay = 1)	0.0072	
Second step threshold (Delay = 2)	0.0302	
Lower Regime	D(EUAFUT)	D(PRODIND)
Constant	0.0346***	0.0555***
	(0.0007)	(0.0006)
D(EUAFUT)-1	−7.4624e-06***	5.4364e-05
	(4.1612e-07)	(1.1715e-01)
D(PRODIND)-1	−2.5196e-02***	−0.9221***
	(7.3649e-06)	(−0.0004)
D(EUAFUT)-2	1.6839e-02***	5.5582e-05
	(2.4155e-05)	(1.9330e-01)
D(PRODIND)-2	−5.8173e-02***	−0.9687***
	(−6.9728e-06)	(−0.0008)
Higher Regime	D(EUAFUT)	D(PRODIND)
Constant	0.09878***	0.09020***
	(0.0003)	(0.0002)
D(EUAFUT)-1	5.0073e-03***	−0.0938
	(2.7073e-06)	(−0.1770)
D(PRODIND)-1	5.8413e-02***	−0. 0270***
	(3.225e-06)	(−0.0001)
D(EUAFUT)-2	−0.0824***	−0.4474
	(0.0009)	(0.7693)
D(PRODIND)-2	0.0187***	0.3778***
	(0.0007)	(0.0003)

Note EUAFUT stands for the ECX EUA Futures price, and PRODIND for the EU Industrial Production Index. The operator D(.) refers to the log-return transformation of the time series. *** indicates statistical significance at the 1 % level, ** at the 5 % level, and * at the 10 % level. The values between parentheses denote the standard errors of the estimated coefficients

5 Results

Estimation results are presented for a TVAR model containing the CO_2 futures price and the EU industrial production index. The goal of this procedure is to assess the sensitivity of carbon prices relative to macroeconomic activity in the EU, as proxied by the influence of industrial production.

The results from the LR linearity tests are shown in the top panel of Table 4. During the first step, the null hypothesis of linearity is clearly rejected in favor of the presence of one or two thresholds in the data. During the second step, we conclude that the TVAR model with two thresholds is preferable. Table 4 also shows that the threshold value is equal to 0.0072 at delay $d = 1$, and 0.0302 at delay $d = 2$.

To put these values into perspective, Fig. 3 plots the threshold variable and the threshold values for the TVAR model estimated with CO_2 and macroeconomic variables. The threshold variable used is pictured in the top panel. The bottom panels represent, respectively, the ordered threshold variable detected with a trimming parameter of 10 % (see [23]) and the threshold value (as a function of the SSR) results of the grid search procedure.

The TVAR estimates are reproduced in the bottom panels of Table 4. By minimizing the AIC as the usual criterion, the number of lags in the TVAR was set at two (for more details, see [4]). In what follows, we comment on the lower and higher regimes estimates. According to the "macroeconomic approach" defined in Sect. 3.2, the results confirm that significant influences exist between CO_2 futures prices and macroeconomic activity [2, 3, 5, 9–11, 24]. What is new is that these relationships are studied in a nonlinear framework, as advised by [12].

The results are qualitatively similar between the lower- and higher-regimes. Namely, in the lower-regime, we uncover the strong influence on the carbon price coming from the industrial production index, in addition to the autoregressive component. Regarding the sign, we observe logically that during the lower-regime, the (downward sloping) aggregated industrial production index affects negatively the carbon price. On the contrary, there is no "bounce back effect" from the carbon price to the EU industrial production, for which only lagged values of the index are found to be statistically significant (at the 1 % level).

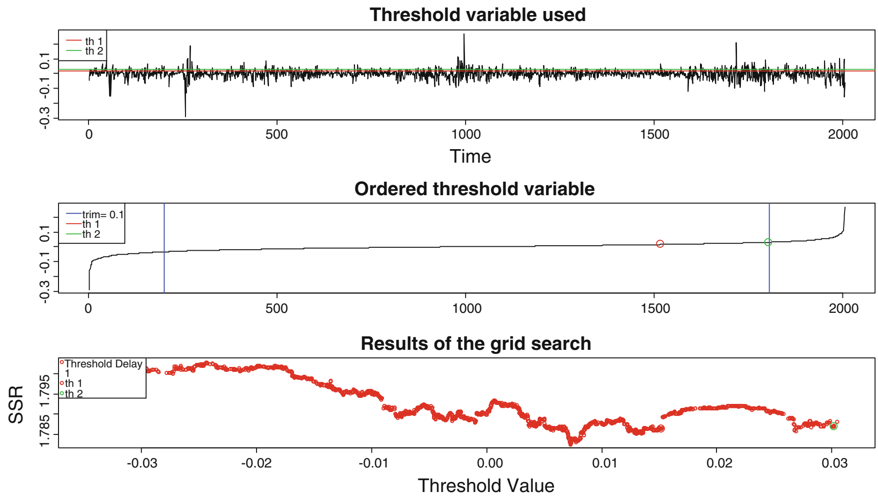

Fig. 3 TVAR estimation results for EUAs and EU industrial production

In the higher-regime, we are able to detect not only the statistical influence of the AR(1) and AR(2) processes on the carbon price, but also of the macroeconomic activity proxy lagged one and two periods (all at the 1 % level). When the industrial production is on the uptake, we detect positive influences on the carbon price, according to the underlying economic mechanisms at stake (as described in Sect. 3.1). Therefore, it seems that the carbon-macroeconomy relationship varies nonlinearly with respect to the threshold identified.

In the lower regime, the carbon price could be related mainly to institutional events (Conrad et al. 2012), while the higher-regime findings are conform to previous literature (see, among others, [25, 21, 26]). Alberola et al. [2] noted previously that the relationship between the carbon price and its main drivers changes before and after the occurrence of structural breaks. We are able to confirm their intuition based on the TVAR nonlinear model, which specifies the presence of several regimes in the data.

Hence, our interpretation in terms of macroeconomic drivers for the carbon market hold both during the lower- and higher regimes, which has been documented recently in the literature [5, 9–11, 24]. Taken together, these results yield to new insights into the relationship between the CO_2 price and the macroeconomy compared to the linear regression framework [2, 3].

5.1 Diagnostic Test

Here, we discuss some formal statistical approaches to model diagnostics via residual analysis [15]. Namely, we consider the generalization of the portmanteau test based on some overall measure of the magnitude of the residual autocorrelations. The dependence of the residuals necessitates the employment of a quadratic form of the residual autocorrelations:

$$B_m = T_{\text{eff}} \sum_{i=1}^{m} \sum_{j=1}^{m} q_{i,j} \hat{\rho}_i \hat{\rho}_j \tag{3}$$

where $T_{\text{eff}} = T - \max(p_1, p_2, d)$ is the effective sample size, (p_1, p_2) are the lag orders, d is the delay parameter, $\hat{\rho}_i$ is the ith lag sample autocorrelation of the standardized residuals, and $q_{i,j}$ some model-dependent constants given in [15]. If the true model is a TVAR model, the $\hat{\rho}_i$ are likely close to zero and so is B_m, but B_m tends to be large if the model specification is incorrect. The quadratic form is designed so that B_m is approximately distributed as χ^2 with m degrees of freedom. In practice, the p-value of B_m may be plotted against m over a range of m values to provide a more comprehensive assessment of the independence assumption on the standardized errors.

Model diagnostics are shown in Fig. 4. The top panel represents the time series plot of the standardized residuals of the TVAR model for EUAs and

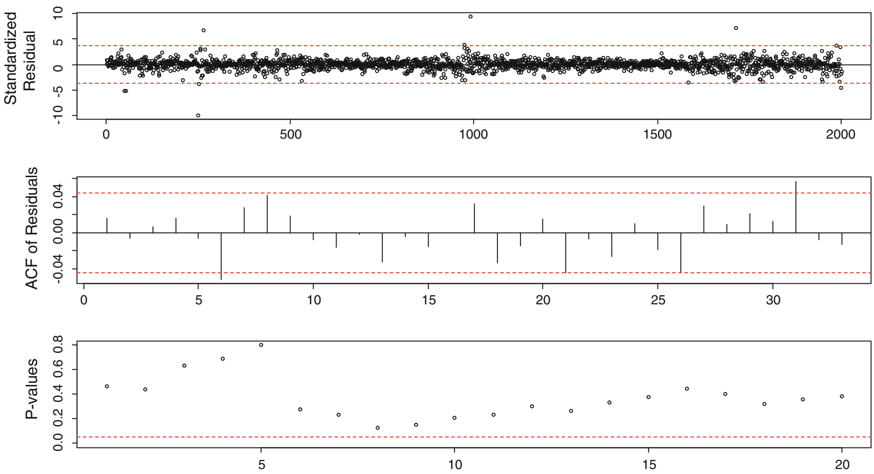

Fig. 4 Residuals autocorrelation for EUAs and EU industrial production

macroeconomic variables. Except for some possible outliers, the plot shows no particular pattern (as the standardized residuals are scattered around zero). The middle panel is the Auto-Correlation Function (ACF) plot of the standardized residuals. The confidence band is based on the simple $1.96/\sqrt{T}$ rule, and should be regarded as a rough guide on the significance of the residual ACF. No lags in the residual autocorrelation are found to be significant. The bottom panel reports the p-values of the more rigorous portmanteau test. The p-values are found to be very large for all m. As no p-value is found to be significant (i.e., we do not reject the null hypothesis of no autocorrelation in the residuals), we may infer that the TVAR model is well-specified.

6 Conclusion

This chapter is dedicated to the analysis of the adjustment between the carbon futures price—taken from the European Climate Exchange—and macroeconomic activity—proxied by the Eurostat EU 27 Industrial Production index. Despite being among the chief carbon price drivers (if not the central), economic activity is indeed often forgotten in empirical studies, which omit it in favor of equity variables (e.g., the Eurostoxx 50 index).

Two main approaches seem to coexist in the literature so far: (i) the "financial markets" approach, and (ii) the "macroeconomic activity" approach. Some scholars have attempted to build mixed equity-macroeconomy strategies. Our central contribution is to recall that, besides energy and institutional variables, there exists a channel of influence, which goes from the state of current production levels (e.g., whether industrial production capabilities are "tense" or "idle") to the carbon price.

The underlying economic logic unfolds as follows: when economic activity (and industrial production taken here as a by-product) increases, then CO_2 emissions mechanically increase (in the absence of short-term energy efficiency gains). This translates ultimately in carbon price increases, *ceteris paribus*. We have been able to verify this relationship in the Threshold VAR framework, with a sample spanning April 2005–January 2013. Extensions of this line of work lie in the field of nonlinear time series econometrics.[12]

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Green Energy Labelling

Josu Lucas and Ibon Galarraga

Abstract This chapter analyses the use of green labelling schemes to promote energy efficiency along the world. Then it estimates the economic value that consumers place on energy efficiency (EE) labels for appliances in the Spanish market. It uses the hedonic method to calculate the price premium paid in the market for that attribute isolated from others. Besides, applies the Quantity-Based Demand System (QBDS) to calculate the own and cross price elasticities of demand for both EE appliances and others. These elasticities are useful for improving the design of policies to promote EE. The chapter looks at three different appliances market in Spain during 2012: washing machines, fridges and dishwashers.

Keywords Energy efficiency · Spain · Labels · Appliances

JEL codes C13 · C20

1 Introduction

Energy efficiency is not an easy issue. There are several barriers to investment in energy efficiency projects. Gillingham et al. [19] identifies them as including energy market failures, capital market failures, innovation market failures, information problems and behavioural failures. Problems related to information deserve special attention.

One way to promote energy efficiency is to solve information problems through the use of energy labelling. There are different types of labels, such as endorsement labelling, comparative labelling and only information labels. The case of comparative

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labels is especially interesting as it is frequently used for durable products such as domestic appliances, cars, houses, or tyres. The European Comparative Energy Label is perhaps the most well-known example of this type of labelling.

Although the European energy label has been analysed in many studies, its impact on consumer behaviour is not widely known. Some studies such as [14, 17, 18] have analysed the willingness to pay (WTP) of consumers for energy efficient refrigerators, dishwashers and washing machines in the Basque Country, and have obtained own and price elasticities of demand.

The present chapter seeks to extend this analysis of the WTP for refrigerators, dishwashers and washing machines to the case of Spain. The aim is to contribute to the literature with new data that can improve the knowledge about energy efficiency and the European energy label.

The chapter is organised as follows: Sect. 1 deals with the importance of information problems when promoting energy efficiency, and the use of labelling schemes to address this barrier. Section 2 briefly discusses the case of energy eco-labels (endorsement labels) and comparative labels, paying special attention to the successful case of the European energy label. Section 3 focuses on one important factor for the success of labelling programmes: consumer's willingness to pay for labelled goods. The cases of washing machines, dishwashers and refrigerators on the Spanish market are analysed. For each appliance, WTP is estimated and an analysis of the price elasticities of demand is included. Elasticity estimates are needed for the design and implementation of policies such as subsidies or taxes devoted to encourage the consumption of labelled goods. The final section is devoted to conclusions.

2 Informational Problems and Policies to Address Them

Information problems consist of, firstly, a lack of information on the part of consumers about the availability of and savings from energy-efficient products, which leads to sub-optimal decisions and under-investment in energy efficiency; secondly, there is the case of asymmetric information, due to manufacturers, retailers and consumers having access to different levels of information, e.g. on the energy performance of a product, and also having different goals or incentives (known as 'split incentives') or actions which are unobservable, enabling them to act opportunistically (known as 'moral hazard'); then there are principal-agent problems, when the agent that has to make the investment is not the one that uses the product bought, and thus has an incentive not to invest in an energy-efficient product, as may happen in the case of landlords and tenants or between different departments within an organisation and finally there are externalities related to learning-by-using [23].

But there are also other behavioural problems which derive from systematic biases in consumer decision-making. These may cover a wide variety of problems such as the following: first loss aversion, because people tend to value the pain of potential losses more highly than the benefit of potential gains [26], which may lead them to decide not to invest in energy efficiency if they are not sure about the savings gained by it; second there is anchoring, because people tend to establish one random point of reference which is very difficult to change and then use it to make comparisons; there is also status quo bias, because deciding to make a change or investment in a new product may require such a big effort that people delay the decision and continue with the situation or product that they already have; then there is the use of heuristics, that allow people to make decisions rapidly, without having to spend a lot of time and energy thinking, but which can result in errors or biases [29]; and finally there is bounded rationality, because people do not tend to act as rationally as they are usually considered to do [23]. All of these behavioural problems are also related to information and the way in which consumers process it.

There are various policy tools that can be implemented individually or in combination to overcome these barriers. The most common are information programmes, taxes and subsidies, Minimum Energy Performance Standards (MEPS) and cap-and-trade programmes. Information programmes are motivated by the existence of informational and behavioural barriers, and they seek to promote energy efficiency investments by providing information about the savings that will result from such investments. Under this approach it is considered that if enough information is given to consumers they will be able to adopt the best choice. However, some studies also show that consumers do not behave rationally in line with the information that they receive, which suggests that there is a gap between information and action, and that family opinion and social pressure are relevant factors in managing information [2].

One information-related policy that has attracted a lot of attention is energy efficiency labelling. Energy labels are informative labels that are affixed to manufactured products and describe a product's energy performance, to provide consumers with the data that they need to make informed purchases [30]. Labels inform consumers about the energy use and costs of appliances and equipment, and enable energy use and efficiency to be compared directly between different models [16, 23]. This reduces the problem that many people face at the time of purchasing, when they are not able to distinguish between energy-efficient products and the rest. Cason and Gangadharan [4] demonstrate in an experiment that reputation and mere talk are not enough to generate efficient outcomes, but that public or private third-party certification can help solve the information problem that consumers have.

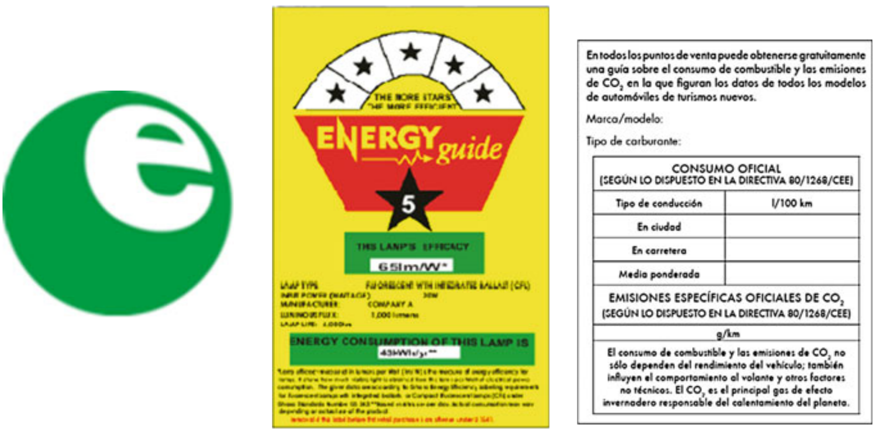
The label is a hybrid instrument, as the existence of a label in a particular market encourages producers to improve the quality and the energy performance of their products. This enables the overall energy efficiency of the market to be increased, given that the least efficient goods will be left out of the market.

Moreover, labelling schemes can be combined with policies of other sorts such as MEPs and subsidies and taxes. In fact, some labels are based on categories of performance that enable governments to subsidise the most energy-efficient classes of products. An example of this policy is the 'Plan Renove' for domestic appliances in Spain. This plan is studied in-depth in [14, 17].

Wiel and Mcmahon [30] distinguishes between three sorts of energy label: endorsement labels, comparative labels and information-only labels. Endorsement labels are used on products that meet or exceed a certain efficiency level, indicating by their presence that the models in question are of superior energy efficiency. Comparative labelling enables consumers to compare the energy performance of two or more models of the same product using either discrete categories of performance or a continuous scale. Finally, information-only labels simply provide data on a product's performance. In some cases, different sorts of labelling may be combined.

Another relevant point is whether the labelling is voluntary or mandatory and whether certification (the right to use the label) is carried out independently or not [22]. Mandatory labelling is generally prescribed by law, and generally enjoys broad recognition and support among consumers [22]. With regard to voluntary labelling, the International Standard Organization (ISO) uses three categories: Type I designates the product of third-party certification programmes that make use of a logo associated with certified products, which are usually government supported; Type II labels consist of one-sided informative environmental claims made by manufacturers and refer to specific attributes of products and Type III use pre-set indices and give quantified information about products based on independent verification [16]. Type I labels are the so-called eco-labels. Therefore, endorsement labels are by definition voluntary labels (Fig. 1).

The effectiveness of a labelling scheme depends on several factors such as the format of the label, the level of market support and the credibility of the labelling programme sponsor [30]. Other factors are consumer awareness and understanding of the labelling, and willingness to pay for a labelled product [8]. Horne [22] argues that the inclusion of consumers, producers and the government in the implementation and management of the label is critical, because more industry-led labels may suffer from lack of trust among consumers. In fact, it is considered that the increased number of voluntary eco-labels in the market place has resulted in



Endorsement Labelling **Comparative labelling** **Information labelling**

Fig. 1 Types of energy labelling

consumer confusion between third-party-certified and self-declared labels [27]. In this sense, some labels not certified by a third party can be vulnerable to claims of greenwashing, affecting the reputation of green firms and their products [8].

3 Types of Energy Labels

3.1 Energy Eco-Labels

There is a wide variety of energy eco-labels around the world. The information that they provide is usually related to best energy performances and the use of renewable resources. There are also other sorts of eco-label that are based on life cycle analysis. These cover all sorts of products, not only those related to energy. In-depth studies of some labels of this type can be found in [1, 21], which analyses labelling around the world.

Perhaps the best-known case of an energy eco-label is the 'Energy Star' programme, launched in the United States in 1992 by the US Environmental Protection Agency (EPA). Energy Star is now present in many countries around the globe, including the EU, Canada, Japan, Taiwan, New Zealand and Australia. This has been made possible by formal international arrangements, through which products approved in one country are licenced to display the label in other participating countries and product information is shared. Although the US founders retain responsibility for developing endorsement criteria, there is a process for consulting all partners when developing new specifications [22].

Energy Star is a voluntary programme run by the US Government which seeks to reduce air pollution and climate change by promoting the use of energy-efficient products. When a manufacturer meets the energy efficiency criteria established by the EPA for a particular product category, it is permitted to show the label in its products and advertisements.

There are various Energy Star programmes: Energy Star for office equipment, the Energy Star Homes programme for building energy-efficient homes and the Energy Star Building programme aimed at commercial buildings, where energy wastage is widespread. The first and best-known programme for office equipment has now been extended to a wide variety of products such as consumer electronics, domestic appliances, heating and cooling systems, lights and lighting, exit signs and transformers [1].

According to the EPA [9] nearly 4 out of 5 US households recognise the Energy Star label, and American consumers have purchased more than one billion energy Energy Star-labelled products, which have resulted in enough energy savings to power 20 million homes. This scheme is thus considered a successful example of energy eco-labelling (Figs. 2, 3).

However, not all eco-labels are successful. In fact, there are good examples of labelling that have not met expectations and have been considered a failure. A case

Fig. 2 Energy star label

Fig. 3 EU eco-label

in point is the EU eco-label, the flower (Fig. 3), which has increasingly been the target of criticism for lax standards, high cost and poor consumer recognition and has even been boycotted by several high profile firms [8]. This EU eco-label is used for over 3000 products (some of them related to energy) with considerable variation in the criteria used in each case. For this reason, the label gives an unclear image of what specific environmental benefits are achieved, and is vulnerable to green-washing. In fact, a 2006 study of EU Member States found that nearly half the people asked stated that they did not know what the label meant [8].

Therefore, as [8] indicates, when choosing an eco-label managers should take into account several factors: (i) choose eco-labels with simple and clear messages to consumers; (ii) choose labels that allocate resources to the communication of their label; (iii) favour multi-product label and (iv) favour labels with endorsements from the government and large retailers.

Other types of energy eco-label from around the world can be found in the following table: (Table 1)

3.2 Comparative Labels: The Eu Energy Label

Practically, all countries around the world manage an energy comparison label for some products, most commonly for domestic appliances, houses and cars. In most cases it is a mandatory label launched by governments, although in some countries the label is voluntary. The design of this kind of label varies considerably from one country to another. Harrington and Damnics [21] distinguishes three types:

- *Dial label*, with greater efficiency linked to advancement along the gauge (more efficient represented by a clockwise arc). This type of label can be found in Australia, Thailand and Korea.
- *Bar label*, which uses a bar chart with a grading from best to worst. All grades are shown on the label, and the one met by the product is indicated. This type of label is used in Europe and South America.
- *Linear label*, which has a linear scale indicating the highest and lowest energy use of models on the market and locating the specific model within that scale. This model is used in North America.

The initial design of the label is important, because it will have an impact on the way that consumers understand it, and because once the label is known by consumers it is very difficult to change it. Moreover, some designs are hard to update when the classes have to be re-scaled.

A good example of the success of this kind of labels is the EU energy label, which is considered responsible for removing the least energy efficient appliances from the market [12]. The EU energy label started with Directive 92/75/CE in 1992 and now covers domestic appliances such as refrigerators and freezers, washing machines, dishwashers and electric ovens. A version of this label is also used for cars, houses, lamps, television sets and air conditioners, and is planned to be extended to more energy products. The label is mandatory for both producers and retailers. Originally it consisted of categories ranging from A (the most energy efficient class) to G (the least), but in the case of domestic appliances the technological change favoured by the label has been so far-reaching that the label has had to be revised and updated, as all the models for some appliances were rated as A. Thus, after long debates and discussions which showed the need for a more dynamic process for including future technical innovations [30], in 2011 the label for refrigerators, dishwashers and washing machines was updated, covering classes from A+++ to D. (Directive 2010/30/EU).

The debate to revise the labelling was launched in 2007, when there was ample evidence that most of the appliances on the market were rated A [13]. The process

Table 1 Some energy eco-labels around the world

LABEL	DESCRIPTION
'100 % Energia Verde'	This is an EU/international and national voluntary label (which originated in Italy)
	It has international value and is based on the RECS (Renewable Energy Certificate System) certificates, which guarantee that the energy used is from renewable sources. The label qualifies energy producers and traders and customers based on their commitment to the environment and seeks to create a voluntary market system to improve the production of energy from RES
'AENOR'	This is a Type I eco-label system aimed at recognising environment-friendly products or services in Spain. The certification procedure is based on auditing and lab testing. The programme marks those products with the lowest environmental impacts. It is mainly aimed at consumer products
'Group for Energy Efficient Appliances Label'	A forum of representatives of European national energy agencies and government departments working with industry on voluntary information activities in the field of energy-efficient home electronics, office equipment and IT-equipment
'Blue Angel'	The Blue Angel was started up by the German government and is awarded by an independent Jury to products that are environmentally friendly
	Each label specifies that the product or service focuses on one of four different protection goals: health, climate, water and resources
	The Blue Angel Standard is managed by four entities: The Environmental Label Jury, The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and The Federal Environment Agency. RAL gGmbH is the label-awarding agency
'OK Power'	The 'Öko-Institut', 'World Wide Fund for Nature' (WWF) Germany and the Consumer Agency NRW have set up the association 'EnergieVision e.V.', which issues the 'ok-power' label in Germany
	The 'ok-Power' label has existed since 2000. The label guarantees the expansion of renewable power plants over and above the requirements of the Renewable Energy Law (REL). The criteria are reviewed by independent accredited laboratories every year, which gives the label high credibility

(continued)

Table 1 (continued)

LABEL	DESCRIPTION
'Energy Saving recommended'	This label originates from the United Kingdom. It is a quick and easy way to spot the most energy-efficient products on the market. Under the Energy Saving Trust Recommended scheme only products that meet strict criteria on energy efficiency can carry the label
'EKOenergy'	EKOenergy is an international eco-label for electricity based in Finland. In addition to being 100 % renewable it also satisfies additional sustainability criteria. The EKOenergy label relies on market principles to increase the share of sustainable energy production
'RECs International Quality Standard'	The 'RECS Good Practice' label certifies electricity from renewable sources as a product to be supplied and/or as a product to be consumed. Since electricity cannot be tracked on the electricity market its sources and the consumption must be certified. An auditing and verification process, based on tradeable green certificates, guarantees the quality of the product and excludes double selling and counting
	Information on carbon emissions based on an LCA and information on sustainability of the electricity source can be included
'Green E-energy'	The Green-e Energy certification assures consumers and businesses in the US and Canada that they are reducing the environmental impact of their electricity use
	Green-e Energy was established in 1997 in order to provide consumer protection in the emerging and unregulated voluntary renewable energy market through clear guidelines, disclosures and standards
	The non-profit Center for Resource Solutions administers the programme
'China Energy Conservation Program' (CECP)	It is a voluntary programme aiming to save energy and reduce emissions by encouraging manufacturers to produce more resource-efficient products and helping consumers to make more sustainable purchase decisions
'Energy Label, Taiwan ROC'	This is a label implemented in Taiwan to promote the deployment of energy efficiency technologies and application of market incentive mechanisms, as well as to encourage manufacturers to invest in research and development of high energy-efficiency products

Source Ecolabel index [10]

was hard, and entailed consulting producers, consumers and environmental NGOs. The result was three different projects supported by different interest groups. The European Commission, producers and some Member States such as Germany, Italy, Poland and Spain supported the idea of an 'open approach', where new categories could be added above class A (with different formats such as A-20 and A-40 %, or A+ and A++). However the European Parliament, environmental NGOs and consumers favoured re-scaling the A-G scale and changing the valuation parameters to adapt them to the new situation of improved energy efficiency on the market. After deadlocks and many bureaucratic problems, Directive 2010/30/EU was eventually enacted in 2010, and a label scheme based on an A+++ to D scale was adopted [13, 30]. This highlights the importance of getting the label design right before launching it, and also the need to reduce bureaucratic barriers to facilitate the promotion of innovations (Figs. 4, 5).

Despite these problems, EU energy labelling is well-known among consumers, and is considered responsible for the technical innovation undergone in Europe, which reduced electrical consumption by electrical white goods by 12 % between 1995 and 2005 [3].

4 Analysis of Willingness to Pay for Efficient Domestic Appliances in Spain

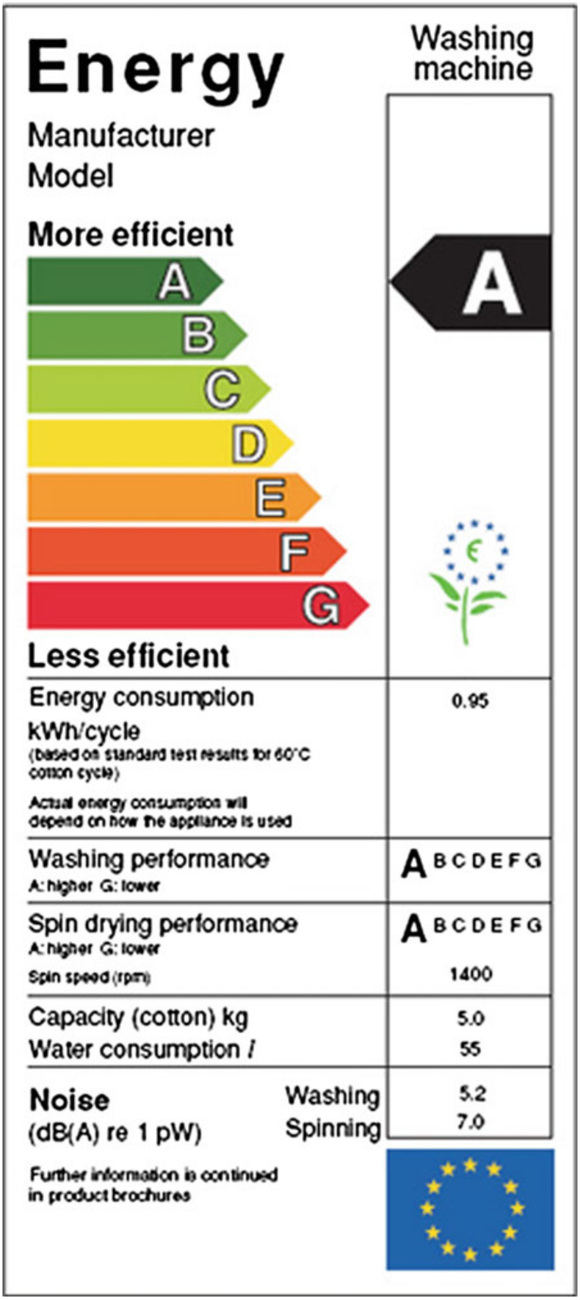
This section seeks to show the importance of willingness to pay for efficient goods, and how labelling can help consumers to identify this attribute of a product. In particular, the cases of three major domestic appliances in Spain are analysed: refrigerators, washing machines and dishwashers. As Spain is an EU Member State, use of EU energy labelling is mandatory. This is tantamount to an indirect analysis of the effectiveness of this label. We also use a demand system method to estimate the elasticities of demand for these appliances with a view to improving the information available on this issue, and therefore the effectiveness of the design of policies to supplement a label scheme.

The data analysed in this chapter were collected in January 2012 from 11 different retailers in 6 regions of Spain by the company *CPS, Estudios de Mercado y Opinión S.L.* Those regions were Galicia, the Basque Country, Valencia, Seville, Madrid and Barcelona. Attributes vary from one type of appliance to another, so the variables collected from each appliance differ too. For this reason, each type is taken in isolation for the analysis.

4.1 Washing Machines

The data contain 1,876 observations for washing machines. 27 producers sell 39 different brands of washing machines on the Spanish market. Table 2 below shows the variables taken into account in this analysis. Other variables have been excluded because of lack of information for some models (power, residual humidity,

Fig. 4 Labelling applied until 20 December 2011



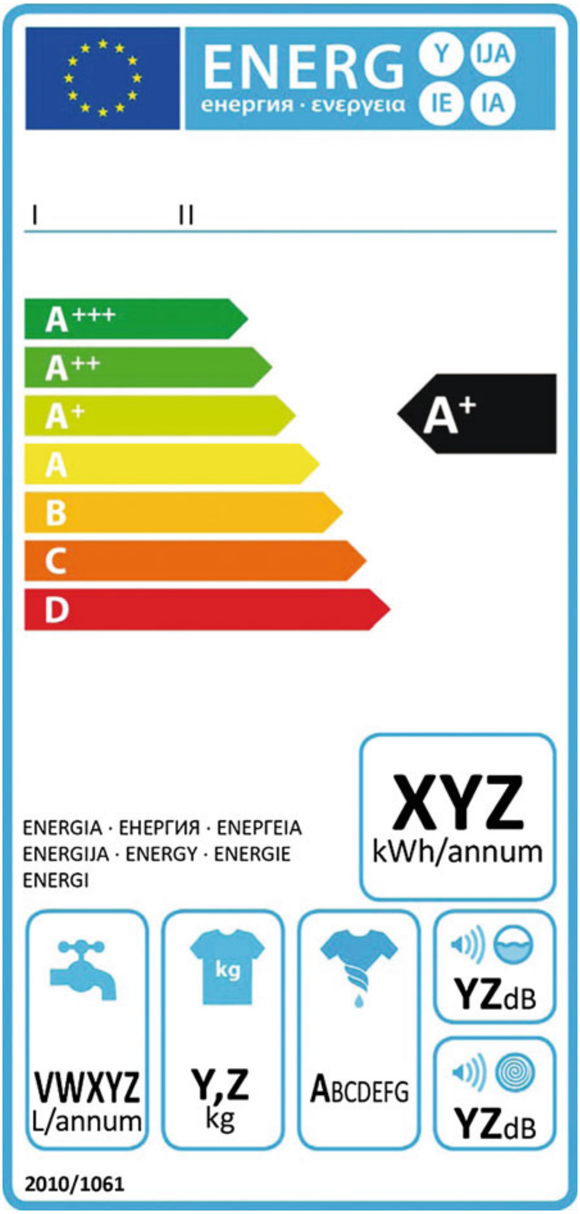


Fig. 5 New labelling applied since 20 December 2011

controls), or because they were not found to be significant in the first estimations (energy and water consumption). As a result, 1,814 observations are finally used. Table 3 shows the main descriptive statistics for each variable.

The average price is €477.44, 10.44 % of the washing machines in the sample have class A*** labelling, while 91 % have class B or C in spin drying

Table 2 Variables selected and their description

Variable	Description
Price (P)	Measured in Euros
Location dummy (L1-L6)	If this location = 1; otherwise = 0
Retailer dummy (R1-R11)	If this retailer = 1; otherwise = 0
Brand dummy (B1-B39)	If this brand = 1; otherwise = 0
Energy labelling dummy (A***)	If energy labelling is A*** = 1; otherwise = 0
Spin drying performance A dummy	If sdpA = 1; otherwise = 0
Spin drying performance B dummy	If sdpB = 1; otherwise = 0
Spin drying performance C dummy	If sdpC = 1; otherwise = 0
Spin drying performance D dummy	If sdpD = 1; otherwise = 0
Spin speed	Measured in revolutions per minute
Height	Measured in millimetres
Width	Measured in millimetres
Depth	Measured in millimetres
Capacity	Measured in kilograms
Colour white dummy	If white = 1; otherwise = 0

Table 3 Main descriptive statistics

Variable	Mean	Standard Deviation	Min	Max
P	477.449	173.668	179.000	1895.00
A***	0.104478	0.305961	0.000000	1.00000
sdpA	0.0656182	0.247681	0.000000	1.00000
sdpB	0.497289	0.500128	0.000000	1.00000
sdpC	0.417028	0.493201	0.000000	1.00000
sdpD	0.0168113	0.128599	0.000000	1.00000
Spin speed	1135.90	153.460	500.000	1600.00
Height	849.329	8.63272	800.000	965.000
Width	574.240	62.6717	400.000	686.000
Depth	572.213	37.6484	425.000	785.000
Capacity	7.09600	1.15656	5.00000	12.0000
White	0.893801	0.308176	0.000000	1.00000

The descriptive statistics for the location, the retailer and the brand can be found in Table A1 in Appendix 2

performance. Their average height is 849 mm; the average width is 574 mm; the average depth is 572 mm and 89.38 % of washing machines are white.

To estimate the effect of energy efficiency on price, a hedonic pricing model [5, 29] is applied using the log-linear functional form, as follows:

$$\text{lprice}_i = \alpha + \beta \sum x_i + \varepsilon_i \tag{1}$$

Table 4 Model estimation

	Coefficient		
const	**7.25951** (0.597484)	[a]	
sdpB	−**0.100122** (0.0287652)	[a]	
sdpC	−**0.133373** (0.035283)	[a]	
sdpD	−**0.11889** (0.0473514)	[b]	
Spinspeed	**0.000271783** (6.53098e-05)	[a]	
height	−**0.00201544** (0.000673553)	[a]	
width	−**0.00110405** (9.26362e-05)	[a]	
depth	**0.000607877** (0.000159054)	[a]	
capacity	**0.119305** (0.00635293)	[a]	
white	−**0.193398** (0.0143089)	[a]	
A***	**0.0415435** (0.0127833)	[a]	
R-squared	0.765241	R-squared corrected	0.757068

[a] Indicates significant at 1 % significance level
The estimated values for the variables Location, Retailer and Brand dummies can be found in Table A2 in Appendix 2

where lprice is the log of the price, Xi is a vector that contains the independent variables which show the attributes of the washing machines and ε is an error term. The Ordinary Least Square (OLS) method is used with robust White standard deviations to avoid potential problems of heteroscedasticity. The main results are shown in Table 4.

The results show a significant, positive effect of class A*** labelling on price, measured at 0.0415, which means that washing machines labelled as class A*** cost 4.15 % more than the others. For an average price of €477, this means that the monetary value of A*** labelling is €19.79.

Another variable of interest is spin drying performance, which is significant, and seems to have a mean difference of 10 % between classes A and B, and 13 % between classes A and C.

This analysis can be completed by estimating the elasticities of washing machines with class A***, and the rest with lower energy efficiency. The Quantity-Based Demand System (QBDS) is used for this purpose as explained in Galarraga et al. [14]. (See Appendix 1).

This model treats the market for appliances as divided into two sorts of goods which are substitutes. One good, L, is the appliance with high energy efficiency and the other good, O, is the appliance with low energy efficiency. Taking into account the presence rates of each sort of appliance in the market, and the share of expenditure that households devote to the purchase of appliances, the expenditure shares of each good can be calculated. These shares, obtained using data from the Instituto Nacional de Estadística (INE),[1] are:

[1] www.ine.es.

Table 5 Own and cross elasticities of demand (washing machines)

	QDBS (Income elasticity = 0.4)		
Price elasticity of demand own O/O	cross O/L	own for 'L'	cross L/O
−0.5	0.1000	−1.2243	0.8243
−0.75	0.3500	−3.2851	2.8851
−1	0.6000	−5.3459	4.9459
−1.25	0.8500	−7.4066	7.0066
−1.5	1.1000	−9.4674	9.0674
−1.75	1.3500	−11.5282	11.1282

$$WO = 0.001492 \quad WL = 0.000181 \quad WX = 0.998326$$

An income elasticity of 0.4 is considered, following Dale and Fujita [6], who suggest that the income elasticity of demand for domestic appliances could be close to 0.5, and [20], who measure it for dryers at 0.26. Additionally, it is also assumed that the own-price elasticity for low energy-efficiency washing machines is in the range of −0.5 to −1.75. The results of the estimation are presented in Table 5.

As can be observed, high energy-efficiency washing machines are more elastic than low-efficiency ones. The own elasticity of demand for high energy-efficiency machines ranges from −1.2 to −11.5, and the impact of a one per cent change in the price of low-efficiency washing machines on the demand for high-efficiency washing machines ranges from 0.82 to 11.1, depending on the assumed own-price elasticity of demand for low energy-efficiency appliances.

4.2 Refrigerators

The data cover 2209 refrigerators produced by 33 different manufacturers and sold by 47 different brands. The variables included are shown in Table 6 below. The percentage of fridges classed as A*** in the sample was very low (0.18 %), so thus A** and A*** have been merged into a single High Class A.

The descriptive statistics can be observed in Table 7. The average price of a refrigerator is €684, but the range is wide, almost €2,467. The percentage of refrigerators with High Class A is 6.30 and 54.94 % are white.

Table 8 shows the results of the estimation.

The results show that products carrying the AHigh label are on average 12.63 % more expensive than those with the low class energy-efficiency label for refrigerators. For an average price of €684, this means that the price premium of high energy-efficiency is €86.39 in the case of refrigerators.

Table 6 Variables selected and their description

Variable	Description
Price (P)	Measured in Euros
Location dummy (L1-L6)	If this location = 1; otherwise = 0
Retailer dummy (R1-R11)	If this retailer = 1; otherwise = 0
Brand dummy (B1-B39)	If this brand = 1; otherwise = 0
Energy labelling dummy AHigh (A*** + A**)	If energy labelling is A*** or A** = 1; otherwise = 0
Height	Measured in millimetres
Width	Measured in millimetres
Depth	Measured in millimetres
Colour white dummy	If white = 1; otherwise = 0

Table 7 Main descriptive statistics

Variable	Mean	Standard deviation	Min	Max
P	684.454	298.699	132.000	2799.00
Height	1820.76	224.731	500.000	2067.00
Width	614.153	79.6390	440.000	960.000
Depth	631.225	41.7874	440.000	770.000
White	0.549431	0.497664	0.000000	1.00000
AHigh	0.0630672	0.243139	0.000000	1.00000

The descriptive statistics for the location, the retailer and the brand can be found in Table A3 in Appendix 2

Table 8 Model estimation

	Coefficient		
const	**3.72337** (0.128229)	[a]	
Height	**0.000550754** (3.74114e-05)	[a]	
Width	**0.0017101** (0.000144917)	[a]	
Depth	**0.00133327** (0.000292875)	[a]	
White	−**0.147167** (0.00881035)	[a]	
AHigh	**0.12633** (0.0245919)	[a]	
R-squared	0.795812	R-squared corrected	0.789523

[a] Indicates significant at 1 % significance level
[b] Indicates significant at 5 % significance level
[c] Indicates significant at 10 % significance level
The coefficients for the location, the retailer and the brand can be found in Table A4 in Appendix 2

Table 9 Own and cross elasticities of demand

	QDBS (Income elasticity = 0.4)		
Price elasticity of demand own O/O	cross O/L	own for ‘L’	cross L/O
−0.5	0.1000	−1.7146	1.3146
−0.75	0.3500	−5.0010	4.6010
−1	0.6000	−8.2875	7.8875

Similarly, the expenditure shares obtained from the percentages of refrigerators in the sample and the data from the INE are:

$$WO = 0.001262 \quad WL = 0.000096 \quad WX = 0.998643$$

In the case of refrigerators an income elasticity of demand of 0.4 is considered, and an own-price elasticity of demand for low energy-efficiency refrigerators in the range of −0.5 to −1. The results can be seen in Table 9. The QBDS imposes some restrictions on the model that require a different range of values to be assumed. These restrictions can be relaxed with the use of the Almost Ideal Demand Model (AIDS) originally developed by Deaton and Muellbauer [7], as explained in [17].

4.3 Dishwashers

The number of dishwashers in the sample is 1,034, although only 988 were found to be suitable for the analysis. The variables used are described in Table 10.

The percentage of dishwashers in the sample classed as A*** is only 0.39 %, which is too low to provide good estimates. A pooled class, AHigh, is therefore used which merges classes A** and A***.

Table 10 Variables selected and their description

Variable	Description
Price (P)	Measured in Euros
Location dummy (L1-L6)	If this location = 1; otherwise = 0
Retailer dummy (R1-R11)	If this retailer = 1; otherwise = 0
Brand dummy (B1-B39)	If this brand = 1; otherwise = 0
Energy labelling dummy AHigh (A*** + A**)	If energy labelling is A*** or A** = 1; otherwise = 0
Acoustic power (AcPow)	
Width	Measured in millimetres
Depth	Measured in millimetres
Number of cutleries (NCut)	
Number of programmes (NProg)	
Colour white dummy	If white = 1; otherwise = 0

Table 11 Main descriptive statistics

Variable	Mean	Standard Deviation	Min	Max
P	482.039	459.000	199.000	1378.00
A high	0.0551257	0.000000	0.000000	1.00000
AcPow	49.4136	49.0000	41.0000	57.0000
Width	573.385	600.000	446.000	640.000
Depth	595.590	600.000	450.000	710.000
NProg	5.43254	5.00000	3.00000	13.0000
NCut	11.8820	12.0000	6.00000	15.0000
White	0.570450	1.00000	0.000000	1.00000

The descriptive statistics for the location, the retailer and the brand can be found in Table A5 in Appendix 2

Table 11 shows the main descriptive statistics for each variable. As can be seen, the average price is €482, while the range is about €1,119. The percentage of dishwashers with class Ahigh is 5.51 and 57 % of the dishwashers in the sample are white.

The estimation results are shown in Table 12.

Thus, dishwashers classed as AHigh are on average 4.03 % more expensive than others with classes A or A*, all else being equal. For an average price of €482 this means that the value of this class of energy-efficiency is €19.42.

The expenditure shares calculated are:

$$WO = 0.001578 \quad WL = 0.000096 \quad WX = 0.998326$$

The income elasticity of demand considered is 0.4 while the price elasticities of demand for low-efficiency dishwashers could range from −0.5 to −1.25 according to the relevant literature [20, 25]. The results can be seen in Table 13.

Table 12 Model estimation

	Coefficient			
const	**8.43836** (0.262729)	a		
AcPow	**−0.0295622** (0.00290575)	a		
Width	**−0.0013798** (0.00017369)	a		
Depth	**−0.000956752** (0.000280104)	a		
NCut	**0.041252** (0.00786865)	a		
White	**−0.131303** (0.00901895)	a		
NProg	**0.0203996** (0.00706321)	a		
AHigh	**0.0403683** (0.0200753)	b		
R-squared	0.823932	R-squared corrected		0.813915

[a] Indicates significant at 1 % significance level

[b] Indicates significant at 5 % significance level

The coefficients related to the location, the retailer and the brand can be found in Table A6 in Appendix 2

Table 13 Own and cross elasticities of demand

	QDBS (Income elasticity = 0.4)		
Price elasticity of demand own O/O	cross O/L	own for ‘L’	cross L/O
−0.5	0.1000	−2.0437	1.6437
−0.75	0.3500	−6.1531	5.7531
−1	0.6000	−10.2625	9.8625
−1.25	0.8500	−14.3719	13.9719

As can be seen, the own elasticity of demand for high energy-efficiency dishwashers ranges from −2.0 to −14.3. Moreover, the impact of a one per cent change in the price of low-efficiency dishwashers on the demand for high energy-efficiency dishwashers ranges from 1.6 to 13.9.

5 Conclusions

Energy labelling can be considered as a powerful tool for promoting energy efficiency. In this sense, different sorts of labelling—endorsement or comparison, voluntary or mandatory—can be used at the same time for different products, although care must be taken not to confuse or tire consumers. Moreover, the design, implementation and management of a label is an important factor of the success of the label, inter alia.

On the other hand, the hedonic pricing analysis presented above has demonstrated that consumers value energy efficiency in the appliance market, but that the differences between high-efficiency classes and class A are not very great. This may be because consumers feel that an appliance with class A is efficient enough, since this was the best class a year ago. Given that the subsidy paid in Spain’s Plan Renove is much higher than the price premiums estimated, it may be held that this policy is not being efficient and should be revised.

Finally, the own and cross price elasticities of demand estimated show that there is still a way of promoting financial or fiscal incentive policies to encourage the purchase of high-efficiency domestic appliances.

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Appendix 1: Quantity-Based Demand System, QBDS

The market for an appliance is assumed to be divided into two subtypes of appliance: those with a 'high' energy-efficiency label and those with a 'low' label. The rest of the characteristics of the machines are equal. So in this case the following variables are defined:

V_i demand for quality *i* (energy efficiency) of good *V* (appliance) in comparable units. That is,
P_i price of quality *i* of good V
M total expenditure
P aggregate price of good V
w_j expenditure share of good V

The demand for quality *i* of good *V* is thus defined as

$$\frac{V_i}{V} = \beta_i \left(\frac{P_i}{P}\right)^{-\infty} \tag{2}$$

Where $\beta_i \geq 0$ is a constant, and $\alpha \geq 0$ is the price sensitivity parameter.

Furthermore, a price index P is defined as

$$P = \prod_i P_i^{s_i}$$

where $s_i \geq 0$ and

$$\sum s_i = 1 \tag{3}$$

And the aggregate demand for all quality types as

$$V = A\left(\frac{P}{M}\right)^{-\mu} \tag{4}$$

s_i is the weight of a quality *i* good in the price index for good *V*. A > 0 is a constant and μ is the expenditure sensitivity parameter for the aggregate demand for the good.

It can be confirmed that the demand for each quality i for good V is homogenous of degree zero in prices and income and that the price elasticity $\in_{ii}$ is given by

$$\in_{ii} = -\alpha + (\alpha - \mu)s_i \tag{5}$$

And the cross price elasticity for good i with respect to the price of good j, $\in_{ij}$, is given by

$$\in_{ij} = (\alpha - \mu)s_j \tag{6}$$

Finally it is noted that the Slutsky equation requires

$$\frac{s_j}{s_i} = \frac{w_j}{w_i} \tag{7}$$

Which can be satisfied locally by selecting the values of s appropriately.

If the budget constraint is now differentiated with respect to M, the additivity condition is obtained as follows:

$$\sum_i w_i e_i = 1 \tag{8}$$

This system is similar to Deaton & Muellbauer's [7] AIDS demand system, though that system is not defined in terms of expenditure shares, but rather of quantity shares. It has the limitation of requiring quantities to be broadly comparable, but the advantage that subgroups of close substitutes are easier to handle, and one can derive plausible own and cross price elasticities from limited data.

Although the QBDS is easier and less demanding than the AIDS, it also has to meet an additional condition: the income elasticity for close substitute goods has to be the same. It is reasonable to expect all the cross price elasticities of close substitutes to be positive. Thus, one can derive the following conditions from the homogeneity restriction:

If $e_i > |e_{i1}|$ then $\sum_j e_{ij} < 0$ for all $j \neq i$. Therefore at least one of the cross price elasticities has to be negative, and

If $e_i < |e_{i1}|$ then $\sum_j e_{ij} > 0$ for all $j \neq I$, and thus, all the cross price elasticities could be positive.

This condition could be simplified by the fact that information on the composite good is not required. Having $e_i < |e_{i1}|$, which can be further simplified to $\bar{\alpha} > \mu$ suffices for there to be positive cross price elasticities for all close substitutes. In sum, this implies that the income elasticity of demand has to be smaller than the own-price elasticity of demand of one of the substitute goods in absolute value.

Appendix 2

(Tables A1, A2, A3, A4, A5, A6)

Table A1 Main descriptive statistics for location, retailers and brand (washing machines)

Variable	Mean	Standard deviation
L1 Galicia	0.146055	0.353256
L2 Basque Country	0.179104	0.383542
L3 Valencia	0.188166	0.390949
L4 Seville	0.170576	0.376238
L5 Madrid	0.162047	0.368592
L6 Barcelona	0.154051	0.361094
T1 Alcampo	0.0954158	0.293867
T2 MediaMarkt	0.337420	0.472956
T3 Carrefour	0.123667	0.329289
T4 Worten	0.135394	0.342236
T5 Miro	0.0890192	0.284847
T6 Eroski	0.0570362	0.231974
T7 Bermudez	0.0175906	0.131493
T8 Saturn	0.0549041	0.227854
T9 ElCorteInglés	0.0714286	0.257608
T10 Expert	0.00159915	0.0399680
T11 Milar	0.0165245	0.127515
M1 AEG-ELECTROLUX	0.0405117	0.197209
M2 ANSONIC	0.000533049	0.0230879
M3 ANTARTIK	0.000533049	0.0230879
M4 APELL	0.00159915	0.0399680
M5 HOTPOINT-ARISTON	0.0218550	0.146249
M6 ASPES	0.0106610	0.102728
M7 BALAY	0.0602345	0.237984
M8 BEKO	0.000533049	0.0230879
M9 BENAVENT	0.000533049	0.0230879
M10 BOSCH	0.0730277	0.260251
M11 CANDY	0.0559701	0.229925
M12 CARREFOUR HOME	0.00692964	0.0829776
M13 COMFEE	0.00106610	0.0326424
M14 CORBERÓ	0.00213220	0.0461388
M15 DAEWOO	0.0255864	0.157940
M16 DE DIETRICH	0.00159915	0.0399680
M17 ECRON	0.00213220	0.0461388
M18 EDESA	0.0463753	0.210353
M19 ELEGANCE	0.00852878	0.0919813
M20 ESVAM	0.00266525	0.0515709
M21 EUROTECH	0.000533049	0.0230879
M22 FAGOR	0.131663	0.338214
M23 HAIER	0.00426439	0.0651803

(continued)

Table A1 (continued)

Variable	Mean	Standard deviation
M24 OTSEIN HOOVER	0.0565032	0.230952
M25 HOOVER	0.00159915	0.0399680
M26 ELECTROLUX	0.0437100	0.204504
M27 INDESIT	0.0581023	0.233999
M28 KUNFT	0.00159915	0.0399680
M29 LG	0.0746269	0.262858
M30 MIELE	0.0223881	0.147981
M31 PANASONIC	0.00319829	0.0564780
M32 SAIVOD	0.00746269	0.0860868
M33 SAMSUNG	0.0570362	0.231974
M34 SIEMENS	0.0479744	0.213769
M35 SMEG	0.00373134	0.0609869
M36 TEKA	0.00799574	0.0890844
M37 WHRILPOOL	0.0708955	0.256719
M38 ZANUSSI	0.0410448	0.198447
M39 BECKEN	0.00266525	0.0515709

Table A2 Estimations for location, retailers, and brand (washing machines)

Variable	Coefficient	Stand. Dev	t-statistic	p	
L2 Basque Country	0.0389672	0.0134474	2.8977	0.00381	***
L3 Valencia	0.00789793	0.0123531	0.6393	0.52268	
L4 Seville	0.0253121	0.012861	1.9681	0.04921	**
L5 Madrid	−0.0136283	0.0143559	−0.9493	0.34259	
L6 Barcelona	0.0215557	0.0133776	1.6113	0.10729	
T2 MediaMarkt	−0.00436503	0.0124692	−0.3501	0.72633	
T3 Carrefour	−0.0055628	0.0163044	−0.3412	0.73301	
T4 Worten	−0.00372588	0.0140642	−0.2649	0.79110	
T5 Miro	0.0984963	0.016526	5.9601	<0.00001	***
T6 Eroski	0.0587101	0.0156516	3.7511	0.00018	***
T7 Bermudez	0.0639205	0.0295434	2.1636	0.03063	**
T8 Saturn	−0.0574855	0.0188037	−3.0571	0.00227	***
T9 ElCorteInglés	0.135949	0.0192525	7.0613	<0.00001	***
T10 Expert	0.107293	0.200332	0.5356	0.59232	
T11 Milar	0.0786691	0.0395448	1.9894	0.04682	**
M3 ANTARTIK	−0.320229	0.0303396	−10.5548	<0.00001	***
M4 APELL	−0.308838	0.0760774	−4.0595	0.00005	***
M5 HOTPOINT-ARISTON	−0.167652	0.040607	−4.1287	0.00004	***

(continued)

Table A2 (continued)

Variable	Coefficient	Stand. Dev	t-statistic	p	
M6 ASPES	−0.172976	0.0347359	−4.9797	<0.00001	***
M7 BALAY	−0.0806951	0.0298303	−2.7051	0.00689	***
M8 BEKO	−0.242431	0.0481439	−5.0356	<0.00001	***
M9 BENAVENT	−0.404878	0.0516738	−7.8353	<0.00001	***
M10 BOSCH	0.0514238	0.0305293	1.6844	0.09228	*
M11 CANDY	−0.109325	0.0300999	−3.6321	0.00029	***
M12 CARREFOUR HOME	−0.268835	0.0366859	−7.3280	<0.00001	***
M13 COMFEE	−0.563127	0.0307365	−18.3211	<0.00001	***
M14 CORBERÓ	−0.131661	0.032358	−4.0689	0.00005	***
M15 DAEWOO	−0.268479	0.0343806	−7.8090	<0.00001	***
M16 DE DIETRICH	0.100114	0.0871205	1.1491	0.25065	
M17 ECRON	−0.306936	0.0381686	−8.0416	<0.00001	***
M18 EDESA	−0.129944	0.0315743	−4.1155	0.00004	***
M19 ELEGANCE	−0.502077	0.0340738	−14.7350	<0.00001	***
M21 EUROTECH	−0.470297	0.0747785	−6.2892	<0.00001	***
M22 FAGOR	−0.0343031	0.0290377	−1.1813	0.23763	
M23 HAIER	−0.236081	0.0439073	−5.3768	<0.00001	***
M24 OTSEIN HOOVER	−0.0883697	0.0324471	−2.7235	0.00652	***
M25 HOOVER	−0.081751	0.100485	−0.8136	0.41601	
M26 ELECTROLUX	0.0101975	0.0324502	0.3143	0.75337	
M27 INDESIT	−0.197175	0.0316602	−6.2278	<0.00001	***
M28 KUNFT	−0.422858	0.0984073	−4.2970	0.00002	***
M29 LG	−0.0182841	0.0382439	−0.4781	0.63264	
M30 MIELE	0.741765	0.0328626	22.5717	<0.00001	***
M31 PANASONIC	0.0302363	0.072096	0.4194	0.67498	
M32 SAIVOD	−0.264099	0.0354476	−7.4504	<0.00001	***
M33 SAMSUNG	−0.121172	0.0327049	−3.7050	0.00022	***
M34 SIEMENS	0.13547	0.0313373	4.3230	0.00002	***
M35 SMEG	0.17567	0.272811	0.6439	0.51971	
M36 TEKA	−0.0894386	0.0526742	−1.6980	0.08969	*
M37 WHRILPOOL	−0.0926054	0.0324102	−2.8573	0.00432	***
M38 ZANUSSI	−0.141419	0.0320704	−4.4097	0.00001	***
M39 BECKEN	−0.39816	0.0442046	−9.0072	<0.00001	***

*Significant at 10% significance level; **significant at 5% significance level; ***significant at 1% significance level

Table A3 Main descriptive statistics for location, retailers and brand (refrigerators)

Variable	Mean	Standard Deviation
L1 Galicia	0.169760	0.375507
L2 Basque Country	0.194658	0.396027
L3 Valencia	0.197374	0.398107
L4 Seville	0.149842	0.356997
L5 Madrid	0.144862	0.352041
L6 Barcelona	0.143504	0.350665
T1 Alcampo	0.0746944	0.262957
T2 MediaMarkt	0.344047	0.475164
T3 Carrefour	0.103667	0.304897
T4 Worten	0.137619	0.344577
T5 Miro	0.106836	0.308974
T6 Eroski	0.0452694	0.207941
T7 Bermudez	0.0267089	0.161268
T8 Saturn	0.0674513	0.250859
T9 ElCorteInglés	0.0701675	0.255487
T10 Expert	0.00226347	0.0475328
T11 Milar	0.0212766	0.144338
M1 AEG-ELECTROLUX	0.0334993	0.179977
M2 HOTPOINT-ARISTON	0.00769579	0.0874072
M3 ASPES	0.00497963	0.0704065
M4 BALAY	0.0534178	0.224916
M5 BECKEN	0.00407424	0.0637140
M6 BEKO	0.00135808	0.0368355
M7 BOSCH	0.0760525	0.265142
M8 CANDY	0.0389316	0.193476
M9 CARREFOUR HOME	0.0104120	0.101529
M10 COMFEE	0.000452694	0.0212766
M11 CORBERÓ	0.00633771	0.0793750
M12 DAEWOO	0.0348574	0.183460
M13 DE DIETRICH	0.00407424	0.0637140
M14 ECRON	0.00769579	0.0874072
M15 EDESA	0.0602082	0.237926
M16 ELECTROLUX	0.0461747	0.209911
M17 ELEGANCE	0.00769579	0.0874072
M18 ESVAM	0.00181077	0.0425243
M19 EUROTECH	0.00543232	0.0735205
M20 EXQUISIT	0.000452694	0.0212766
M21 FAGOR	0.107288	0.309550
M22 HAIER	0.0113173	0.105803
M23 HISENSE	0.00135808	0.0368355

(continued)

Table A3 (continued)

Variable	Mean	Standard Deviation
M24 HOOVER	0.00407424	0.0637140
M25 INDESIT	0.0633771	0.243695
M26 KUNFT	0.00316885	0.0562160
M27 KYMPO	0.000452694	0.0212766
M28 LG	0.0941603	0.292118
M29 LIEBHERR	0.0679040	0.251638
M30 MIELE	0.0135808	0.115769
M31 MYBALAY	0.00181077	0.0425243
M32 NORWOOD	0.000905387	0.0300828
M33 PANASONIC	0.00226347	0.0475328
M34 SAIVOD	0.00543232	0.0735205
M35 SAMSUNG	0.0683567	0.252414
M36 SEVERAL	0.00181077	0.0425243
M37 SEVERIN	0.00181077	0.0425243
M38 SHARP	0.000905387	0.0300828
M39 SIEMENS	0.0507017	0.219437
M40 SMEG	0.00814848	0.0899208
M41 TEKA	0.00679040	0.0821422
M42 TENSAI	0.000452694	0.0212766
M43 VANGUARD	0.000452694	0.0212766
M44 WESTWOOD	0.000905387	0.0300828
M45 WHITE WESTINGHOUSE	0.00362155	0.0600838
M46 WHIRLPOOL	0.0493436	0.216633
M47 ZANUSSI	0.0239928	0.153061

Table A4 Estimations for location, retailers and brand (refrigerators)

Variable	Coefficient	Stand. Dev	t-statistic	p	
L2 Basque Country	0.0632133	0.0178257	3.5462	0.00040	***
L3 Valencia	0.0321248	0.0139628	2.3007	0.02150	**
L4 Seville	0.0341917	0.0141975	2.4083	0.01611	**
L5 Madrid	0.0431768	0.0169523	2.5470	0.01094	**
L6 Barcelona	0.0413875	0.0149085	2.7761	0.00555	***
T2 MediaMarkt	0.0407181	0.0213245	1.9095	0.05634	*
T3 Carrefour	0.0299728	0.0232492	1.2892	0.19747	
T4 Worten	0.0396041	0.0225399	1.7571	0.07905	*
T5 Miro	0.0909524	0.0235457	3.8628	0.00012	***
T6 Eroski	0.0150963	0.0298867	0.5051	0.61353	

(continued)

Table A4 (continued)

Variable	Coefficient	Stand. Dev	t-statistic	p	
T7 Bermudez	0.0720643	0.0364132	1.9791	0.04794	**
T8 Saturn	0.0293243	0.0257403	1.1392	0.25474	
T9 ElCorteInglés	0.181768	0.0283183	6.4187	<0.00001	***
T10 Expert	0.161605	0.103329	1.5640	0.11797	
T11 Milar	0.0390694	0.0353885	1.1040	0.26971	
M2 HOTPOINT-ARISTON	−0.419308	0.081028	−5.1748	<0.00001	***
M3 ASPES	−0.307396	0.0356946	−8.6118	<0.00001	***
M4 BALAY	−0.178103	0.027889	−6.3861	<0.00001	***
M5 BECKEN	−0.457842	0.0338363	−13.5311	<0.00001	***
M6 BEKO	−0.397844	0.0570477	−6.9739	<0.00001	***
M7 BOSCH	−0.021943	0.028019	−0.7831	0.43363	
M8 CANDY	−0.287942	0.0312219	−9.2225	<0.00001	***
M9 CARREFOUR HOME	−0.491218	0.0383342	−12.8141	<0.00001	***
M10 COMFEE	0.427415	0.0496321	8.6117	<0.00001	***
M11 CORBERÓ	−0.493611	0.0341462	−14.4558	<0.00001	***
M12 DAEWOO	−0.472967	0.0316291	−14.9535	<0.00001	***
M13 DE DIETRICH	0.0835603	0.0497823	1.6785	0.09340	*
M14 ECRON	−0.5339	0.0551673	−9.6778	<0.00001	***
M15 EDESA	−0.302501	0.0278071	−10.8786	<0.00001	***
M16 ELECTROLUX	−0.0757218	0.0370042	−2.0463	0.04085	**
M17 ELEGANCE	−0.65165	0.0627134	−10.3909	<0.00001	***
M18 ESVAM	−0.64533	0.0395066	−16.3348	<0.00001	***
M19 EUROTECH	−0.548656	0.0427469	−12.8350	<0.00001	***
M20 EXQUISIT	−0.406128	2.9302	−0.1386	0.88978	
M21 FAGOR	−0.105422	0.0261036	−4.0386	0.00006	***
M22 HAIER	−0.513856	0.0695364	−7.3898	<0.00001	***
M23 HISENSE	−0.579277	0.137648	−4.2084	0.00003	***
M24 HOOVER	−0.4937	0.0981807	−5.0285	<0.00001	***
M25 INDESIT	−0.440609	0.0306288	−14.3854	<0.00001	***
M26 KUNFT	−0.551497	0.0400949	−13.7548	<0.00001	***
M27 KYMPO	−0.0733194	0.0287993	−2.5459	0.01097	**
M28 LG	−0.20566	0.0294761	−6.9772	<0.00001	***
M29 LIEBHERR	0.132956	0.0295279	4.5027	<0.00001	***
M30 MIELE	0.274463	0.0444984	6.1679	<0.00001	***
M31 MYBALAY	−0.373192	0.16085	−2.3201	0.02043	**
M32 NORWOOD	−0.59957	0.0692358	−8.6598	<0.00001	***
M33 PANASONIC	−0.0498537	0.0797589	−0.6251	0.53200	
M34 SAIVOD	−0.510927	0.145506	−3.5114	0.00046	***
M35 SAMSUNG	−0.205813	0.0309577	−6.6482	<0.00001	***

(continued)

Table A4 (continued)

Variable	Coefficient	Stand. Dev	t-statistic	p	
M37 SEVERIN	−0.257007	0.0733404	−3.5043	0.00047	***
M38 SHARP	−0.430325	0.0822236	−5.2336	<0.00001	***
M39 SIEMENS	−0.00517677	0.028145	−0.1839	0.85408	
M40 SMEG	−0.130258	0.103145	−1.2629	0.20678	
M41 TEKA	−0.331209	0.0683998	−4.8423	<0.00001	***
M43 VANGUARD	−0.248279	0.0479215	−5.1810	<0.00001	***
M44 WESTWOOD	−0.658148	0.140814	−4.6739	<0.00001	***
M45 WHITE WESTINGHOUSE	−0.278013	0.0554739	−5.0116	<0.00001	***
M46 WHIRLPOOL	−0.273367	0.0281256	−9.7195	<0.00001	***
M47 ZANUSSI	−0.246607	0.0330347	−7.4651	<0.00001	***

*Significant at 10% significance level; **significant at 5% significance level; ***significant at 1% significance level

Table A5 Main descriptive statistics for location, retailers and brand (dishwashers)

Variable	Mean	Standard deviation
L1 Galicia	0.133462	0.340238
L2 Basque Country	0.166344	0.372570
L3 Valencia	0.200193	0.400339
L4 Seville	0.148936	0.356198
L5 Madrid	0.181818	0.385881
L6 Barcelona	0.169246	0.375150
T1 Alcampo	0.0841393	0.277731
T2 MediaMarkt	0.332689	0.471404
T3 Carrefour	0.134429	0.341278
T4 Worten	0.116054	0.320445
T5 Miro	0.0918762	0.288991
T6 Eroski	0.0464217	0.210498
T7 Bermudez	0.0251451	0.156641
T8 Saturn	0.0676983	0.251349
T9 ElCorteInglés	0.0822050	0.274810
T10 Expert	0.00773694	0.0876614
T11 Milar	0.0116054	0.107153
M1 AEG-ELECTROLUX	0.0647969	0.246286
M2 APELL	0.000967118	0.0310985
M3 ASPES	0.0135397	0.115626
M4 BALAY	0.0764023	0.265769
M5 BOSCH	0.140232	0.347396
M6 BECKEN	0.00290135	0.0538120
M7 BLUESKY	0.000967118	0.0310985

(continued)

Table A5 (continued)

Variable	Mean	Standard deviation
M8 CANDY	0.0367505	0.188240
M9 CARREFOUR HOME	0.00773694	0.0876614
M10 CORBERÓ	0.00386847	0.0621067
M11 DAEWOO	0.00580271	0.0759909
M12 DE DIETRICH	0.00290135	0.0538120
M13 ECRON	0.0116054	0.107153
M14 EDESA	0.0531915	0.224524
M15 ELECTROLUX	0.0705996	0.256279
M16 ELEGANCE	0.00290135	0.0538120
M17 FAGOR	0.168279	0.374294
M18 HOME CARREFOUR	0.00773694	0.0876614
M19 HOTPOINT-ARISTON	0.00580271	0.0759909
M20 INDESIT	0.0454545	0.208400
M21 KUNFT	0.00290135	0.0538120
M22 LG	0.0232108	0.150645
M23 MIELE	0.0348162	0.183403
M24 NORDWOOD	0.000967118	0.0310985
M25 SAIVOD	0.00580271	0.0759909
M26 SAMSUNG	0.00580271	0.0759909
M27 SELECT LINE	0.0106383	0.102642
M28 SIEMENS	0.0473888	0.212572
M29 SMEG	0.0125725	0.111474
M30 TEKA	0.0203095	0.141125
M31 WHIRLPOOL	0.0609284	0.239315
M32 WHITE WESTINGHOUSE	0.00290135	0.0538120
M33 ZANUSSI	0.0483559	0.214621
M34 GAGGENAU	0.000967118	0.0310985

Table A6 Estimations for location, retailers and brand (dishwashers)

Variable	Coefficient	Stand. Dev	t-statistic	p	
L2 Basque Country	0.0397859	0.0163064	2.4399	0.01488	**
L3 Valencia	0.0233408	0.0143378	1.6279	0.10389	
L4 Seville	0.0180421	0.0154505	1.1677	0.24322	
L5 Madrid	−0.00723976	0.0159277	−0.4545	0.64955	
L6 Barcelona	0.037197	0.0155497	2.3921	0.01695	**
T2 MediaMarkt	−0.00603457	0.0146125	−0.4130	0.67972	
T3 Carrefour	0.0693018	0.0190408	3.6397	0.00029	***
T4 Worten	−0.0152746	0.0192584	−0.7931	0.42790	
T5 Miro	0.0876567	0.0186384	4.7030	<0.00001	***

(continued)

Table A6 (continued)

Variable	Coefficient	Stand. Dev	t-statistic	p	
T6 Eroski	0.0745703	0.0187256	3.9823	0.00007	***
T7 Bermudez	0.14968	0.0315102	4.7502	<0.00001	***
T8 Saturn	−0.020249	0.020924	−0.9677	0.33343	
T9 ElCorteInglés	0.143218	0.0183941	7.7861	<0.00001	***
T10 Expert	0.0155095	0.082356	0.1883	0.85067	
T11 Milar	0.0970123	0.0410446	2.3636	0.01831	**
M2 APELL	−0.40673	0.0288589	−14.0937	<0.00001	***
M3 ASPES	−0.271245	0.0388819	−6.9761	<0.00001	***
M4 BALAY	−0.029393	0.0282604	−1.0401	0.29858	
M5 BOSCH	0.0478179	0.0280761	1.7032	0.08888	*
M6 BECKEN	−0.281433	0.0643438	−4.3739	0.00001	***
M8 CANDY	−0.130722	0.0470269	−2.7797	0.00555	***
M9 CARREFOUR HOME	−0.499412	0.0380564	−13.1229	<0.00001	***
M10 CORBERÓ	−0.427511	0.0545997	−7.8299	<0.00001	***
M11 DAEWOO	−0.45207	0.0572378	−7.8981	<0.00001	***
M12 DE DIETRICH	−0.147349	0.120745	−1.2203	0.22265	
M13 ECRON	−0.272183	0.054155	−5.0260	<0.00001	***
M14 EDESA	−0.131679	0.0308893	−4.2629	0.00002	***
M15 ELECTROLUX	0.0141147	0.0257229	0.5487	0.58333	
M17 FAGOR	−0.0273468	0.0259217	−1.0550	0.29171	
M18 HOME CARREFOUR	−0.484519	0.0414191	−11.6980	<0.00001	***
M19 HOTPOINT-ARISTON	−0.187088	0.0553041	−3.3829	0.00075	***
M20 INDESIT	−0.290984	0.0345424	−8.4240	<0.00001	***
M22 LG	−0.1288	0.0580258	−2.2197	0.02668	**
M23 MIELE	0.506637	0.0408137	12.4134	<0.00001	***
M24 NORDWOOD	−0.529087	1.68797	−0.3134	0.75401	
M25 SAIVOD	−0.365334	0.0588595	−6.2069	<0.00001	***
M26 SAMSUNG	−0.0577015	0.0381582	−1.5122	0.13084	
M27 SELECT LINE	−0.603966	0.0345843	−17.4636	<0.00001	***
M28 SIEMENS	0.118675	0.0387393	3.0634	0.00225	***
M29 SMEG	−0.123677	0.0965571	−1.2809	0.20057	
M30 TEKA	−0.234249	0.0409149	−5.7253	<0.00001	***
M31 WHIRLPOOL	−0.129955	0.0305298	−4.2567	0.00002	***
M32 WHITE WESTINGHOUSE	−0.329099	0.147629	−2.2292	0.02604	**
M33 ZANUSSI	−0.157279	0.0298118	−5.2757	<0.00001	***
M34 GAGGENAU	−0.19252	0.0296483	−6.4935	<0.00001	***

*Significant at 10% significance level; **significant at 5% significance level; ***significant at 1% significance level

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Estimating the Direct Rebound Effect in the Residential Energy Sector: An Application in Spain

Pablo Gálvez, Petr Mariel and David Hoyos

Abstract This chapter estimates the direct rebound effect in residential heating and domestic hot water services in Spain in 2012. The fuels analysed are electricity and natural gas. Contrary to previous research, the direct rebound effect is calculated using, among others, data on unit variable cost of energy, the amount of energy consumed per annum and residential CO_2 emissions. The direct rebound effects estimated are found to be relatively high, so an increase in energy efficiency can be expected to produce only a slight decrease in consumption. On the other hand, it is found that a decrease in residential CO_2 emissions may result in a drop in residential energy consumption, with natural gas as the most sensitive fuel.

Keywords Direct rebound effect · CO_2 emissions · Residential energy demand · Heckman model

JEL code Q41 · Q54 · Q55

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1 Introduction

Since the Kyoto Protocol was drawn up in 1997, numerous European countries have committed to reducing greenhouse gas emissions as a way of mitigating climate change. In this context, energy efficiency has a fundamental role to play, since it enables such emissions to be reduced without affecting individual welfare and economic development.

In Spain, the residential sector is a good candidate for the design of policies to promote the efficient use of energy. According to EUROSTAT data, between 1990 and 2011 the residential sector was the third largest energy consumer after industry and transport, with a share of almost 17 % of the total energy consumed. Moreover, household energy demand grew during that period at a relatively steady rate of around 4 % per annum.

According to IDAE[1] (Spanish Institute for Diversification and Energy Saving), homes that use only electricity heating and domestic hot water account for 67 % of total energy consumption. These results corroborate the data presented by Freire-González [5] for homes in Catalonia in 2003, which show the proportion of residential energy use devoted to heating & hot water to be 62.3 %.

The strategies most widely used to promote energy efficiency in the residential sector include mainly information campaigns, subsidies for the replacement of less-efficient appliances by newer ones that consume less, energy labelling of domestic appliances and the recently approved Royal Decree 235/2013, which establishes a "basic procedure for the energy certification of new and existing buildings". The obligations introduced under this decree include the provision of reports on residential CO_2 emissions and energy rating for buildings.

Thanks to this new regulation, families now have more information when they buy or rent a home. A dwelling with lower CO_2 emissions or a higher energy rating is assumed to be more energy efficient, which means that they should spend less on heating than for a dwelling with higher emissions and a lower rating.

However, not all the increase in energy efficiency in dwellings or any other production system is translated into cost savings. This is due to the so-called "rebound effect". Indeed, this effect may be large enough to exceed the maximum expected cost savings from technological improvements.

According to Berkhout et al. [1] and Sorrell et al. [15], there are three types of rebound effect[2]: the "direct rebound effect" or first-order response is the substitution effect that arises from a reduction in the cost of service provided by a more energy efficient system. It affects only the system, and can be seen in the case of families

[1] For more information see the final report on the project SPAHOUSEC, Análisis del Consumo Energético del Sector Residencial en España, available at en http://www.idae.es/.

[2] Sorrell & Dimitropoulos [14] propose a parallel rebound effect in regard to time. An interesting paper that analyses this time rebound effect in the main household activities is that of Brencic and Young [3].

who keep their heating on for longer after replacing their old heating system by a more energy efficient one.

The "indirect rebound effect", or second-order response, is the income effect that arises from an increase in the real income of an individual as a result of the use of a more efficient technology. This income may be used for other activities which, of course, may entail energy consumption, so total energy demand may increase.

Effects on the economy as a whole, or the third order response, involve the adjustments that take place in markets related to technological change. Thus, an increase in energy efficiency changes production costs and therefore market equilibrium of all the goods related to the technological improvement.

Greening et al. [7] argue that there is also a fourth effect, which they call the "transformational effect", which includes all potential changes in human activities that could potentially increase or decrease energy consumption in the wake of a technological improvement. They cite changes in the use of time and in the structure of labour forces as cases in point.

There is a growing body of literature aiming at estimating the direct rebound effect including, particularly, the paper by Roy [13], which demonstrates that in homes which replace kerosene lighting by more efficient systems based on solar energy, consumption of kerosene decreases by only between 20 and 50 % of the amount initially expected. This can be explained in terms of previously unmet demand for lighting, lower costs paid by individuals who instal more efficient appliances with the aid of government subsidies and low levels of coordination between energy-saving policies and energy prices.

The papers by Brännlund et al. [4] and Mizobuchi [11] apply a model called the Linear Approximate Almost Ideal Demand System. Both these papers calculate the direct rebound effect as the difference in CO_2 emissions between the situation with and without the direct rebound effect, i.e. when the expected energy savings are achieved in full.

The paper by Brännlund et al. [4] simulates the effect of a 20 % increase in energy efficiency in transport services and lighting on emissions of CO_2, sulphur dioxide (SO_2) and nitrogen oxides (NOx). The results show an increase in gas emissions of around 5 % and a rebound effect of more than 12 % after technological improvement. The authors conclude that an increase of 130 % in the taxes levied on CO_2 emissions would cancel out those emissions, reduce SO_2 output and increase NOx emissions.

Mizobuchi [11] highlights the role of capital costs in calculating the direct rebound effect. The key assumption is that more energy efficient appliances have higher capital costs than less-efficient ones. The results in the paper show that if capital costs are ignored the direct rebound effect is 115 %, which implies that an increase in energy efficiency actually increases CO_2 emissions. However, the direct rebound effect drops drastically to 27 % when capital costs are included.

A major review of the literature on the direct rebound effect can be found in the paper by Sorrell et al. [15]. In regard to heating, the authors conclude that there would be a direct rebound effect of 20 %, while for the case of domestic hot water they mention only the result obtained by Guertin et al. [8], who estimate a direct rebound effect of between 34 and 38 %.

Along with their review, Sorrell et al. [15] identify the following sources of bias in the estimation of rebound effects: (1) failing to consider other significant costs apart from the cost of energy itself that may form part of the system, e.g. capital, maintenance and time; (2) long periods of high energy prices, which could make households more sensitive in regard to energy consumption; and (3) possible endogeneity in energy efficiency.

Perhaps the only author to have analysed this issue in Spain is Freire-González [5], who estimates the rebound effect from services arising from the use of electricity in homes in Catalonia to be 35 % in the short term and 49 % in the long-term. His paper uses aggregate economic and weather data affecting the municipalities of Catalonia between 1999 and 2006 as control variables.

Most papers reviewed coincide in regard to the mechanisms that generate the rebound effect, and focus their attention on estimating the direct effect. To estimate higher order responses, more detailed information on the activities of the members of the household are required, along with data on their interaction with markets. Such data are not always available. Moreover, none of the papers reviewed uses residential CO_2 emissions as a control variable in direct rebound effect models.

Accordingly, the present chapter sets out to provide more information on the direct rebound effect in the residential sector in Spain, using detailed data on each household and its consumption drawn up in 2012. An attempt is also made to link the characteristics of each household, represented by CO_2 emissions, with energy consumption in the form of electricity and natural gas.

A distinctive feature of the chapter is that it uses detailed information on energy consumption in each household. This includes the use of variable costs per kWh of electricity and natural gas, the rated electrical power and the total payment for the electricity and natural gas consumption in 2012 by each household. The papers reviewed use average prices to represent residential energy costs.

The findings of this study are particularly interesting given that in 2012 Spanish households were experiencing an adverse economic situation. According to the INE (Spain's National Institute of Statistics) the unemployment rate was 25 % and the price index for residential fuel (electricity, gas and others) rose by 7.3 percentage points more than the overall price index. Moreover, the INE‘s Living Conditions Survey reveals that in 2011 around 17 % of Spanish households stated that they had not felt warm enough in winter [10].

The chapter has two objectives: (1) to estimate the direct rebound effect based on an improvement in energy efficiency of heating and domestic hot water systems fired by electricity and natural gas; and (2) to estimate how the change in residential CO_2 emissions affects fuel consumption. In the first of these objectives it is assumed that residential energy demand is explained largely by heating and domestic hot water provision.

The results may be useful in designing policies to promote the efficient use of energy and reductions in residential CO_2 emissions. For instance, knowing how much domestic electricity consumption is likely to decrease with a given reduction in residential CO_2 emissions can help to assess whether investments in household improvements will prove cost-effective.

The chapter comprises five sections. Besides the introduction, Sect. 2 describes the methodology used. Section 3 describes the data used in estimating the direct rebound effect. Section 4 presents the results obtained. Finally, Sect. 5 interprets the results and sets out the main conclusions reached.

2 Methodology

2.1 The Direct Rebound Effect Theory

Sorrell and Dimitropoulos [14] describe a household as a system which uses energy (E), capital, time and other resources to produce a set of services for its members, such as heating, safety, protection, luxury and others. Such systems are characterised by their energy efficiency, i.e. by their ability to transform incoming energy into final services. The energy efficiency, ε, can be defined as follows:

$$\varepsilon = \frac{S}{E}, \tag{1}$$

where S is the useful work of the system, which is the unit of measurement of the services produced. It must be pointed out that the same service can have more than one useful work measurement; for example, residential heating could be measured in terms of the surface area of the dwelling or the number of individuals to whom the services provided.

The elasticity of energy consumption with respect to energy efficiency, $\eta_\varepsilon(E)$, can be expressed as follows:

$$\eta_\varepsilon(E) = \frac{\partial E}{\partial \varepsilon}\frac{\varepsilon}{E}. \tag{2}$$

By substituting (1) into (2), one obtains:

$$\eta_\varepsilon(E) = \eta_\varepsilon(S) - 1, \tag{3}$$

where, $\eta_\varepsilon(S)$ is the demand efficiency elasticity of useful work as well as the term that defines the direct rebound effect. From (3) it can be observed that if the direct rebound effect is zero, an increase in energy efficiency results in an equivalent decrease in energy demand.

To determine the sign of the rebound effect, demand costs must be analysed. If the only significant cost is that of energy then the cost of useful work is defined as follows:

$$P_S = \frac{P_E}{\varepsilon}, \tag{4}$$

where, P_E is the price of energy. From (4) it can be seen that an increase in the energy efficiency of the system, with P_E being fixed, reduces the cost of useful work and should therefore increase demand for the services produced. This shows that $\eta_\varepsilon(S)$ will always be positive. If $0 < \eta_\varepsilon(S) < 1$, the increase in energy efficiency produces energy savings. When, $\eta\varepsilon(S) > 1$, a situation known as "backfire" occurs, i.e. an increase in ε results in an increase in energy consumption E.

From (4) it can be observed that an increase in ε has the same effect on the cost of useful work as a decrease in P_E, *ceteris paribus*. This condition, known as symmetry, taken together with the assumption that P_E is exogenous (the assumption under which the price of energy is not related to changes in energy efficiency) turns Eq. (3) into:

$$\eta_\varepsilon(E) = -\eta_{P_S}(S) - 1. \tag{5}$$

This new way of calculating the rebound effect, defined as the price elasticity of the useful work of the demand for energy services, is useful when there is not enough variation in energy efficiency in the data. However, this definition could give rise to problems due to the difficulty in obtaining an objective measurement of S. One way of overcoming this problem is to assume not just symmetry and exogeneity but also that energy efficiency is constant. This turns expression (5) into the following:

$$\eta_\varepsilon(E) = -\eta_{P_E}(E) - 1 \tag{6}$$

The rebound effect is now measured in terms of the price elasticity of energy demand. This expression requires that the demand for fuel, for which the price elasticity is obtained, be closely linked to the service whose energy efficiency is improved.

2.2 The Models

If the assumptions of symmetry, exogeneity and constant energy efficiency are met and the demand for residential fuel is linked to heating and domestic hot water services, the direct rebound effect for those services is obtained by estimating the residential demand for electricity and natural gas.

Given that electricity consumption is observed at all the households in the sample, demand for electricity is analysed via a classical regression model. Similarly, given that natural gas is only consumed at 38.9 % of the households in the sample, demand for gas is estimated using the model proposed by Heckman [9].

The Heckman model, also known as the selectivity model or tobit type 2 model, begins by formulating the following regression model to represent the consumption equation:

$$y_i = x_i'\beta + \varepsilon_i \tag{7}$$

where, the sub-index i refers to each individual and the dependent variable y_i represents any variable that cannot be observed in the whole population.[3] The explanatory variables of the model are represented by x_i and β. The random term is represented by ε_i. The Heckman model also requires a selection variable z^* such that y_i is observed only if z^* exceeds a set threshold, e.g. zero. This variable is explained by the following selection equation:

$$z^* = w_i'\gamma + u_i, \tag{8}$$

where, the vector w_i contains the explanatory variables that affect the selection, the vector γ of unknown coefficients, and u_i is the random error term.

Assuming the errors ε_i and u_i have a normal bivariate distribution with mean zero and correlation ρ, one can write:

$$\begin{aligned} E[y_i|y_i observed] &= E[y_i|z^* > 0] \\ &= E[x_i'\beta + \varepsilon_i|w_i'\gamma + u_i > 0] \\ &= x_i'\beta + E[\varepsilon_i|w_i'\gamma + u_i > 0] \\ &= x_i'\beta + E[\varepsilon_i|u_i > -w_i'\gamma] \\ &= x_i'\beta + \rho\sigma_\varepsilon \left[\frac{\phi\left(\frac{w_i'\gamma}{\sigma_u}\right)}{\Phi\left(\frac{w_i'\gamma}{\sigma_u}\right)} \right], \end{aligned} \tag{9}$$

where, the standard deviations of the errors are, from equations (7) and (8), σ_ε and σ_u. The expressions $\phi(\cdot)$ and $\Phi(\cdot)$ represent the density and probability functions, respectively, of the standard normal distribution. In most instances, it is supposed that σ_u is equal to unity as the variable z^* cannot be observed. Therefore, Eq. (9) corresponds to Eq. (7) with an additional explanatory variable called the inverse Mills ratio evaluated at $w_i'\gamma$. Note that γ is replaced with Probit estimates from the first stage (8).

From Eq. (9) it can be seen that if ε_i and u_i are independent ($\rho = 0$), the second term on the right hand side would be zero, so the consumption equation could be estimated directly by ordinary least squares (OLS). On the other hand, if $\rho \neq 0$, Eq. (9) could be estimated by the two-stage estimation procedure in Heckman [9], or by maximising the following likelihood function [6]:

[3] In this paper y_i is residential natural gas consumption.

$$\ln L = \sum_{y_i=0} \ln\left[\Phi\left(-w_i'\gamma\right)\right] + \sum_{y_i > 0} \ln\left[\sigma_\varepsilon^{-1}\phi\left(\frac{y_i - x_i'\beta}{\sigma_\varepsilon}\right)\right] + \\ + \sum_{y_i > 0} \ln\left[\Phi\left(\frac{w_i'\gamma + \rho\sigma_\varepsilon^{-1}(y_i - x_i'\beta)}{\sqrt{1-\rho^2}}\right)\right] \quad (10)$$

3 Data

The data used here were obtained via a survey designed especially for this study,[4] which was conducted early in 2013 in the cities of Bilbao, Vitoria, Madrid, Malaga and Seville. This survey revealed the demographics of each household, the characteristics of each dwelling and specific information on residential energy consumption in 2012.

The selected residential fuels were electricity and natural gas, mainly because these are the leading fuels for residential power systems. According to IDAE, in 2010 they accounted between them for 60 % of all residential energy. Moreover, selecting these two fuels rather than LPG or domestic fuel-oil enabled us to obtain more precise information on their annual consumption and costs. Each household provided data on exactly how many kWh of electricity and natural gas it consumed, the unit cost per kWh, its rated electrical power and the invoicing periods recorded in 2012.

Residential CO_2 emissions and energy ratings were obtained via CE3X (Version 1.0), a software package developed for IDAE in line with the directives of Royal Decree 235/2013. Given that the data entered into CE3X require expert technical knowledge of the thermal envelope and other building characteristics,[5] it was necessary to identify variables on which we were likely to receive answers but which were at the same time sufficiently representative to provide a good basis for calculating residential CO_2 emissions and energy rating. Fortunately, C3EX is highly flexible and is capable of working with just one household dataset.

The input variables used were the following: the postcode of the dwelling, the age of the building or the date of the latest major refurbishment (year planning permission was granted), the surface area of the dwelling, whether it was part of a block, whether it was on the top floor, access to solar energy, use of air conditioning, nature of the main appliances used to provide heating and hot water (and fuel used for that purpose). Respondents were also asked to include data on the

[4] This survey was conducted under the EC "Public health impacts in URban environments of Greenhouse gas Emissions reduction strategies (PURGE)" project, FP7-ENV-2010.

[5] For more information see the CE3X User's Manual for the Energy Rating of Existing Buildings, available on the website of the Spanish Ministry of Industry, Energy and Tourism at http://www.minetur.gob.es/.

orientation, surface area and shading of the main facade, what percentage of it was made up of glass, the type of glass used and the type of window frames.

The survey was initially conducted on 1,507 households. To minimise the effect of outliers, actual annual spending on each fuel was compared to an approximate figure for annual expenditure calculated on the basis of unit costs and a fixed term plus VAT tax. This enabled those households in which the difference between the 2 measures of spending lay below percentile 10 and above percentile 90 to be eliminated from the sample. Any household which failed to provide part of the information required for the study was also eliminated. This resulted in a final sample comprising 820 households.

Table 1 shows the main sources of energy used for heating and domestic hot water in the sample households. Households are grouped into 3 geographical areas: the northern area comprises Bilbao and Vitoria, the central area comprises Madrid and the southern area comprises Malaga and Seville.

The data show that the fuel most widely used for heating in the northern and central areas is natural gas, followed by electricity. In the northern area the third most widely used fuel is domestic fuel oil, while in the central area it is LPG (gas canisters). The area with most heating systems installed is the northern area, where 97.7 % of households have heating.

In the southern area the number one fuel is electricity, which is used by 77.2 % of households. In fact, no other fuel accounts for more than 3 % of households. It is noteworthy that 17.6 % of the households in the southern area state that they use no heating system.

All the households in the survey indicate that they have domestic hot water systems. Once again, natural gas and electricity are the main fuels used in the northern and central areas, while in the south the main fuels are LPG, electricity and natural gas. Other energy sources such as coal and bio-fuels have no significant presence as residential fuels anywhere in the sample.

Table 1 Residential fuel use by region

Proportion of homes by fuel	North (215 households)		Centre (259 households)		South (346 households)	
	Heating	Domestic hot water	Heating	Domestic hot water	Heating	Domestic hot water
Natural Gas	60.0	62.3	47.1	52.1	0.9	15.0
Fuel-oil	15.8	13.5	7.3	5.8	0.0	0.0
Electricity	19.1	20.9	27.0	25.9	77.2	24.9
LPG	2.3	3.3	9.3	15.1	2.9	59.2
Other sources	0.5	0.0	1.2	1.2	1.4	0.9
No service	2.3	0.0	8.1	0.0	17.6	0.0

LPG = Liquefied petroleum gas. "Other sources" = bio-fuel, biomass/renewables and coal
Source Own work

Table 2 CO_2 emissions (in kg CO_2/m^2 per year) in households using electricity or natural gas for heating and hot water use

Residential fuel	N	Avg CO_2	Sd	Min	Max
Electricity	146	38.89	24.02	10.04	114.78
Natural gas	253	19.91	9.08	5.87	52.38

Note Avg CO_2 = Average CO2 emissions, Sd = Standard deviation, Min = Minimum and Max = Maximum
Source Own work

Table 2 reveals that homes which use electricity as their sole source of energy emit more CO_2 on average than those that use natural gas. In the latter there is also less dispersion, and they account for almost 100 observations more than households that use only electricity.

Table 3 sums up the results provided by CE3X. Energy ratings range from A (most efficient) to G (least efficient). As expected, as the energy rating moves towards G the average CO_2 emissions increase in all 3 areas. However that increase is not linear: indeed, the average CO_2 emissions from households rated G are more than 10 times greater than the average from the most efficient households.

The data indicate that the energy ratings of dwellings in all three areas are mainly concentrated at levels C, D and E. Between them these three labels account for 75.8 % of the northern households in the sample, 81.5 % of the central households and 91.6 % of those from the south. The smallest group in the sample is that of the households with the lowest average CO_2 emissions.

It is noteworthy that some households with different energy ratings may in fact have similar CO_2 emission levels. For instance, households labelled D in the North and E in the South have quite similar average CO_2 emissions. This is because the rating procedure penalises some households because of their location.

Table 4 shows the variables in the study along with some descriptive statistics. The data show that, on average, households have three members, and at least one occupant is employed. In the sample, 36.6 % of household heads are women, 38 %

Table 3 Household energy rating and CO_2 emissions (in kg CO_2/m^2 per year)

Label	North		Centre		South	
	Share	Avg CO_2	Share	Avg CO_2	Share	Avg CO_2
A	1.4	7.15	1.2	5.20	0.3	3.63
B	11.6	12.11	8.5	9.92	1.7	5.67
C	24.7	16.78	20.8	14.32	11.0	8.16
D	24.7	23.48	28.6	22.83	33.8	14.53
E	26.5	40.40	32.0	39.77	46.8	26.24
F	3.3	54.25	1.9	63.47	2.3	39.15
G	7.9	83.23	6.9	93.66	4.0	50.21

Note Avg CO_2 = Average CO_2 emissions
Source Own work

Table 4 Variables and descriptive statistics of the sample

Variable	Mean	Sd	Min	Max
Natural gas consumption	4801.535	3464.492	141	20648
Natural gas price	0.054	0.007	0.029	0.130
Electricity consumption	2810.529	1654.557	29	21079
Electricity price	0.147	0.007	0.107	0.175
Number of members	2.722	1.180	1	7
Number of persons in work	1.283	0.870	0	5
Household head retired	0.213	0.410	0	1
Household head female	0.366	0.482	0	1
Household head w/primary education	0.321	0.467	0	1
Household head w/secondary education	0.380	0.486	0	1
Household head w/higher education	0.299	0.458	0	1
Income <€1,500/month	0.449	0.498	0	1
Income €1,500–2,500/month	0.380	0.486	0	1
Income >€2,500/month	0.171	0.377	0	1
Surface area of dwelling	86.477	34.433	25	500
Number of rooms	4.591	1.455	1	12
Rented dwelling	0.177	0.382	0	1
Home with electric oven	0.789	0.408	0	1
Number of TV sets	2.027	0.963	0	6
Home with tumble dryer	0.148	0.355	0	1
Home with dishwasher	0.507	0.500	0	1
Rated electrical power	3.899	1.049	1.1	10.4
2-monthly electricity bill	0.541	0.499	0	1
Dwelling in northern area	0.262	0.440	0	1

Note The statistics for "natural gas consumption" and "natural gas price" are calculated on the basis of the number of homes that use natural gas, i.e. 327 observations. The sample for all the remaining variables contains 820 observations. The variables "natural gas (full)" and "electricity (full)" represent those households which have heating and domestic hot water systems fired by natural gas and electricity, respectively. Energy consumption is measured in kWh, and prices correspond to the variable unit costs measured in Euros/kWh. CO_2 emissions are measured in kg CO_2/m^2 per annum. Surface area is measured in m^2

Source Own work

have average education and 29.9 % have a university or higher education qualification. Around 45 % of the households in the sample have monthly incomes of less than €1,500.

In the sample, 17.8 % of households use electricity for heating and hot water, while 327 households use natural gas, of which 77.4 % (30.9 % of the total sample) use gas for both heating and hot water. On average, each household in the sample has two TV sets; 78 % have electric ovens, almost half have dishwashers, although only 14.8 % have tumble dryers. The average dwelling measures 86.5 m^2 and has five rooms.

4 Results

This section presents the results of the residential demand models for electricity and natural gas. The demand for electricity is estimated via OLS, while the Heckman model for natural gas is estimated via maximum likelihood. In both cases, robust standard errors are used. It is important to note that CO_2 emission variable contains information about the physical characteristics of each dwelling, including its location.

4.1 Demand for Electricity

Table 5 shows the results for two linear regression models analysing residential demand for electricity. The difference between them lies in the presence of two interaction terms in panel (b).

The term *natural gas* (*full*) × ln (*natural gas price*) estimates the cross elasticity between electricity and natural gas. The term *electricity* (*full*) × ln (*electricity price*) serves to estimate the price elasticity of electricity demand in two groups of households: those that use electricity as their sole fuel (*electricity* (*full*)) and those that combine electricity with other sources of energy for providing heating and domestic hot water. In panel (a) the variables *electricity price* and number of rooms are significant at the 10 % level. The variables number of TV sets, *household with tumble dryer, rated electrical power in household, 2-monthly electricity bill* and *CO_2emissions* are significant at the 1 % level.

Residential electricity consumption increases by 13.9 % per additional household member, and by 2.9 % per additional room. A household with a tumble dryer can be expected to consume 17.9 % more electricity than a household without one. Electricity demand also increases by 10.8 % per additional TV set. A unit increase in the rate electrical power would increase electricity consumption by 10 %. Households with 2-monthly electricity billing are found to consume 28 % less electricity than those that are billed monthly.

In relation to energy efficiency related variables, electricity demand price elasticity is found to be −0.722, which means that demand is inelastic. Thus, if the assumptions of symmetry, exogeneity and constant efficiency are met the direct rebound effect should be 0.722. Therefore, according to (6) an increase of 10 % in the energy efficiency of electrically powered heating and domestic hot water systems results in a reduction in electricity consumption of just 2.78 %.

The CO_2 emissions variable is found to have the expected sign—the lower the dwelling quality rating, the higher are its CO_2 emissions and heating demand. For a 10 % reduction in CO_2 emissions, the electricity consumption is reduced by just 0.98 %.

Table 5 Residential demand for electricity

Explanatory variables	(a) Explained variable: ln (electricity consumption)		(b) Explained variable: ln (electricity consumption)	
	Coef.	p-value	Coef.	p-value
ln (electricity price)	−0.722*	(0.053)	−0.708*	(0.055)
Household size (pers)	0.139***	(0.000)	0.138***	(0.000)
Number of working persons	−0.018	(0.544)	−0.019	(0.499)
Household head female	−0.042	(0.347)	−0.030	(0.490)
Household head w/secondary education	−0.061	(0.209)	−0.075	(0.121)
Household head w/higher education	−0.033	(0.512)	−0.067	(0.182)
Income €1,500–2,500/month	0.029	(0.558)	0.052	(0.288)
Income >€2,500/month	0.023	(0.720)	0.062	(0.326)
ln (surface area of dwelling)	−0.075	(0.349)	−0.117	(0.140)
Number of rooms	0.029*	(0.068)	0.045***	(0.004)
Dwelling rented	0.063	(0.259)	0.019	(0.730)
Household with electric oven	0.083	(0.146)	0.126**	(0.026)
Number of TV sets	0.108***	(0.000)	0.099***	(0.000)
Household with tumble dryer	0.165***	(0.001)	0.165***	(0.001)
Household with dishwasher	0.006	(0.893)	0.030	(0.450)
Rated electric power in household	0.100***	(0.000)	0.076***	(0.000)
2-monthly electricity bill	−0.329***	‘(0.000)	−0.295***	(0.000)
ln(CO_2 emissions)	0.098***	(0.003)	0.020	(0.562)
Natural gas (full) × ln (natural gas price)			0.046***	(0.007)
Electricity (full) × ln (Electricity price)			−0.158***	(0.000)
Constant	5.426***	(0.000)	5.848***	(0.000)
Observations Adjusted Ff	820		820	
	0.250		0.293	

Dependent variable: log (*electricity consumption*)
Note *($p < 0.10$), **($p < 0.05$), ***($p < 0.01$)

In the model shown in panel (b), the significant variables are mostly the same ones found in panel (a), though they are joined by *household with electric oven* and the two interaction terms. In this model, each additional room increases electricity consumption by 4.5 %. Possession of an electric oven increases electricity consumption by 13.4 % and the *2-monthly electricity bill* variable decreases consumption by 25.5 %, i.e. almost 4 percentage points less than in panel (a).

The new interaction terms in panel (b) are significant at the 1 % level. From *natural gas* (*full*) × log (*natural gas price*) a positive cross elasticity for electricity and natural gas is obtained, which means that the two systems are complimentary.

From the term *electricity* (*full*) × log (*electricity price*) it is observed that households which use only electricity are more sensitive to variations in electricity price than those that combine electricity with other fuels. Demand is inelastic for both groups. Assuming the assumptions of symmetry, exogeneity and constant efficiency are met, the direct rebound effect for households with more than one energy source is 0.708, while for households that use only electricity is −0.866 (from the sum of −0.708 and −0.158). Substituting these figures in (6), a 10 % increase in energy efficiency in heating and hot water systems entails electricity savings of 2.92 % in the first group of households, and 1.34 % in the second group.

4.2 Demand for Natural Gas

Table 6 shows the results of the Heckman model applied to the demand for natural gas. The panel (a) shows the coefficients of the consumption model and the panel (b) contains the results of the probit model whose dependent variable represents the use of natural gas.[6] Natural gas heating is hardly used at all in the households in the southern area, so these households are not included in the natural gas model. This reduces the size of the sample to 474 households, 271 of which use natural gas.

The parameter ρ, which represents the correlation between unobserved errors in the selection and demand equations, is significant at 1 %. This finding validates the use of the Heckman model for analysing natural gas demand. Based on the selection model, it is deduced that electricity and natural gas prices are not significant in the choice of natural gas. The variables surface area of dwelling, rented dwelling, CO_2 emissions and household in northern area are found to be significant at 1 %. The first three of these variables negatively affect the choice of natural gas, while the last increases the likelihood of its use.

The variable number of rooms is found to be significant at 5 %, and to increase the likelihood of natural gas being chosen as a residential fuel. The remaining variables, i.e. income €1,500−2,500/month, household with electric oven and household with dishwasher are significant at 10 % and have a positive effect on the choice of natural gas.

Regarding natural gas consumption, the variable surface area of dwelling, which can be interpreted as elasticity, is significant at the 1 % level. Hence, a 10 % increase in the household surface area would increase natural gas consumption by 13.4 %.

Income related variables are significant at least at 10 %. These coefficients indicate that households where the income is more than €1,500/month consume approximately 30 % less natural gas than those with lower incomes.

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[6] For the Heckman model to perform well it is recommendable that at least one variable that only affects selection (in this case of natural gas) should be significant [12]. This paper assumes that owning more electrical appliances may provide an incentive to use electricity along with other energy sources such as natural gas.

Table 6 Residential demand for natural gas

Explanatory variables	(a) Explained variable: ln (natural gas consumption)		(b) Explained variable: 1 if household uses natural gas. 0 otherwise.	
	Coef.	p-value	Coef.	p-value
ln (natural gas price)	−1.094**	(0.035)	−0.440	(0.501)
ln (electricity price)	0.704	(0.546)	−1.250	(0.293)
Household size (pers)	0.038	(0.528)	−0.047	(0.474)
Household head female	−0.106	(0.389)	0.125	(0.377)
Household head retired	−0.148	(0.394)	0.036	(0.847)
Household head w/secondary education	0.160	(0.315)	−0.099	(0.590)
Household head w/higher education	0.106	(0.527)	0.066	(0.747)
ln (surface area of dwelling)	1.342***	(0.000)	−0.944***	(0.001)
Number of rooms	−0.113*	(0.057)	0.123**	(0.046)
Rented dwelling	0.209	(0.384)	−0.865***	(0.000)
Income €1,500–2,500/month	−0.322**	(0.047)	0.299*	(0.068)
Income >€2,500/month	−0.345*	(0.059)	0.341*	(0.063)
ln (CO_2 emissions)	0.512**	(0.022)	−1.150***	(0.000)
Household with tumble dryer			0.102	(0.642)
Household with electric oven			0.301*	(0.090)
Number of TV sets			−0.087	(0.130)
Household with dishwasher			0.216**	(0.041)
Household in northern area			0.267***	(0.010)
Constant	0.176	(0.951)	3.435	(0.281)
ρ	−0.942			
$X_1^2\ (\rho = 0)$	7.81***	(0.005)		
Observations	271		474	

Dependent variable: log (*natural gas use*)
Note *(p < 0.10), **(p < 0.05), ***(p < 0.01)

The variable natural gas price is significant at 5 %, and its level indicates that demand for natural gas is slightly elastic. If the assumptions of symmetry, exogeneity and constant efficiency are satisfied, the direct rebound effect for natural gas is 1.094. Substituting this figure in (6), it follows that a 10 % increase in energy efficiency in natural gas powered heating and domestic hot water systems would entail an increase in natural gas consumption of 0.94 %, i.e. a slight backfire [15].

The variable CO_2 emissions is also significant at the 5 % level, and as with residential demand for electricity, its sign is as expected. However its magnitude is considerably greater. Thus, a 10 % drop in CO_2 emissions results in a 5.12 % decrease in natural gas consumption.

5 Discussion

The purpose of this chapter is to analyse energy efficiency in heating and domestic hot water systems, using CO_2 emissions, a set of demographic variables on each household, energy consumption and the variable unit costs paid by each family for the use of electricity and natural gas in 2012. CO_2 emissions are calculated according to the "basic procedure for the energy certification of new and existing buildings" approved by the Spanish government, a transposition of the European Directive 2010/31/UE [2].

The direct rebound effect obtained for electricity demand in homes that use more than one fuel is estimated at 0.71. This indicates that approximately 29 % of any increase in energy efficiency in residential electrical systems translates into energy savings. Similarly, in homes that use only electricity the rebound effect is higher, i.e. 0.87. This reveals that much of the increase in efficiency in electrical heating and hot water systems is lost due to increases in electricity consumption, i.e. only 13 % would go into energy saving. In respect to the natural gas model the estimated direct rebound effect is 1.094. Thus, increased energy efficiency actually increases natural gas consumption in 0.094 %. This is the opposite of the result that would be expected in the wake of technological improvements.

Obtained direct rebound effects are relatively high in comparison with those published in other papers. This may be due to the economic situation affecting Spanish households in 2012, a year characterised by high unemployment rates and energy price increases 7.3 percentage points higher than the increase in the general consumer price index. Moreover, according to the Living Conditions Survey conducted by the INE (Spain's National Institute of Statistics), almost 17 % of Spanish households admit to not having been warm enough during the previous winter.

Thus, households may have become more sensitive to prices and reduced their energy consumption for heating and domestic hot water [15]. In this scenario an increase in energy efficiency, which decreases the cost of service, results in a greater direct rebound effect, as households seek to revert to their previous comfort levels in consumption for heating and hot water.

However, it must be said that the direct rebound effects estimated here may be overestimated due to the lack of significant information on, for instance, capital, maintenance and time-related costs. According to Sorrell and Dimitropoulos [14] higher service costs result in a drop in demand for services and therefore in smaller rebound effects. Indeed, Mizobuchi [11] demonstrates that when capital costs are considered the direct rebound effect drops from 115 % to just 27 %. Accordingly, the findings reported here may be interpreted as maximum levels of sensitivity of energy consumption to changes in energy efficiency.

Another important point is the possible link between energy prices and energy efficiency. If energy prices increase and remain high for a long period of time, industry may develop more efficient equipment. Such a link would invalidate the assumption of exogeneity, which would mean that the rebound effect measured via energy price elasticity would not be correct. This paper uses cross-section data, under the assumption that the exogeneity hypothesis holds.

A comparison of electricity demand models reveals that once energy sources are controlled for the CO_2 emissions variable ceases to be significant in electricity consumption. The opposite occurs in regards to natural gas, where residential CO_2 emissions are found to have a significant link with consumption.

If the goal is to reduce electricity and natural gas consumption, households should seek to reduce its CO2 emissions by improving some of the characteristics of their dwellings such as the type of glass used, window frames, etc. In fact, using natural gas as an energy source for heating and hot water along with upgrades in building energy efficiency ratings could increase the market value of dwellings.

It can also be concluded that one way of reducing residential CO_2 emissions is to avoid the use of electricity as an energy source for heating and domestic hot water. On the other hand, and looking closer at the selection model, it can be inferred, for instance, that the use of natural gas can be encouraged by increasing household income and informing families who rent their homes of its advantages as a fuel.

To sum up, this chapter provides empirical evidence to support the design of policies with a view to reducing residential energy consumption and residential CO_2 emissions. The direct rebound effects estimated are relatively high, so energy efficiency increases in heating and hot water systems are likely to result in only a slight decrease in energy consumption. Indeed, in the case of natural gas increased energy efficiency results in an increase in consumption (backfire). It is also demonstrated that lower CO_2 emissions are associated with decreases in residential energy consumption, with natural gas being the most sensitive fuel in this case.

Future research could be directed at analysing the trend over time in the direct rebound effect as regards heating and domestic hot water, to check whether changes in energy efficiency are capable of producing greater savings in residential energy consumption under different economic conditions.

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Budget-Neutral Financing to Unlock Energy Savings Potential: An Analysis of the ESCO Model in Barcelona

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Abstract The objective of this chapter is to introduce an increasingly popular business model known as the Energy Service Company (ESCO) model and bring to light the principal barriers to its widespread implementation both from the public and private perspectives. The ESCO model is essentially a "budget neutral" method of financing the purchase, installation and maintenance of energy efficient technologies. This concept, which incorporates notions of "third-party financing" and "energy performance contracting," has been used successfully for quite some time in countries like the USA, the UK, and Germany. In this chapter, we will analyze the possibilities and limitations in the implementation of the ESCO model in a specific case study: the Barcelona municipal area in Spain.

1 Introduction

The growing demand for energy and the necessity to cut global greenhouse gas (GHG) emissions are the two foremost issues related to designing energy and environmental policies [8]. Nowadays, energy consumption accounts for around 85 % of global carbon dioxide (CO_2) emissions worldwide, and it is at the heart of the transformation needed to move towards a low carbon economy. There is now a worldwide concurrence that the development and diffusion of a wide range of new technologies is an important mechanism to confront climate change and energy scarcity.

We would like to express our thanks to all of the interview respondents who took the time to discuss essential issues with us and provide suggestions for our research. They enabled us to form realistic and current perspectives, both from the public and private spheres.

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The International Energy Agency (IEA) estimates that energy efficiency[1] measures can reduce up to 10–15 % of global CO_2 per year at no additional cost [14]. Among the existing abatement options, the replacement of old windows and the introduction of better insulation are considered as two of the most cost-effective short term measures [20]. In fact, if the certain conditions are favorable [16] these investments could promise high positive economic returns [9, 21]. However, private investments in energy efficiency that at first glance might seem economically worthwhile are not always undertaken. This so-called "energy efficiency gap" [15] can be explained by existing barriers such as principal-agent problems, lack of access to capital, insufficient information, among others. Understanding these barriers is very important for the design of effective policies.

The ESCOs model is an interesting instrument that can help to overcome some of the most important barriers mentioned at the same time. An Energy Service Company (ESCO) is a company that is engaged in developing, installing, and financing comprehensive, performance-based projects that improve the energy efficiency or load reduction of facilities owned or operated by customers [2, 23]. ESCOs are seen as an important vehicle for promoting energy efficiency around the world as many case studies show [18, 24, 25]. Recent studies have also shown that the growth potential for the ESCO industry in many different countries is remarkable. For example, based on an a database of nearly 1,500 case studies of energy-efficiency projects, it was estimated that ESCO industry revenues for energy-efficiency related services in the US ranged from $1.8 to $2.1 billion in 2001 and that ESCO revenues increased at an average annual growth rate of 24 % during the last decade [10].

This chapter analyzes the possibilities and limitations in the implementation of the ESCO model for the case study of the Barcelona municipal area in Spain. Our aim is to select the instruments that are recommendable for the further development of the ESCO market based on the experience in other countries and, once we have seen to what extent they are implemented in Barcelona, propose how to unlock this energy savings potential. The methodologies used in our analysis consist of qualitative data collection methods such as content analysis, semi-structured interviews and a case study analysis. The semi-structured format was chosen because it offers a "bottom-up" perspective of the strengths and limitations of existing policies that are designed to foster the use of the ESCO model. However, a comprehensive review of the ESCO market in Catalonia, or a detailed examination of the relevant laws and regulations that apply to this market, is beyond the scope of this analysis.

The chapter is organized as follows: Section 2 introduces the ESCO model and how it can help to overcome the energy efficiency gap. Section 3 outlines the main barriers to the development of this market, taking into account the political and

[1] Energy efficiency and conservation are different concepts. Energy conservation is defined as: "the absolute reduction in energy demand compared to a certain baseline, measured in energy units"; while energy efficiency refers to the improvement in the way energy is used to provide a product or service, and it is measured in units of output per energy unit [19]. What people really consume is not energy, but rather, energy services. Therefore, energy efficiency can help to provide the same level of energy services using a lower amount of energy [1].

economic incentives available in Spain. Section 4 presents the current state of the ESCO market within the Barcelona metropolitan context in the public and the private sector. The final section is devoted to conclusions.

2 The Energy Services Company Model

An Energy Services Company (ESCO) is a tool to enhance the sustainable use of energy through promoting energy efficiency and renewable energy resources. The function of an ESCO is commonly known as Energy Performance Contracting (EPC). In other words, an ESCO takes the financial risk of developing and performing measures for an improvement in energy efficiency, and recovers the investment through the energy cost savings derived from that intervention (see Fig. 1).

Figure 2 depicts how the ESCO assumes the interaction with relevant players, eliminating the need for the client to deal with them. It shows that the ESCO's remuneration is directly linked to the good performance of the various actors. Thus, the maximum energy savings are ensured for the client.

The basic steps of an ESCO project can be divided into two major phases: before and after the installation. At the beginning, a preliminary analysis of energy consumption patterns is carried out to evaluate the savings potential. Then, a detailed technical analysis is executed to detect inefficiencies. If the client decides to continue with the installation, a formal contract is prepared and the project is executed. Once the equipment is operating, a continuous guarantee phase starts and lasts until the contract terminates. During this period, the ESCO monitors the installation and takes any necessary corrective actions. In addition, a clause is usually included stipulating a periodic revision of energy consumption in order to correct for any deviations. For instance, if the actual consumption is less than expected, the energy cost savings may be shared between the ESCO and the client. On the contrary, if the client exceeds the expected consumption, the ESCO may assume the difference or, if stipulated in the contract, the client must pay the difference.

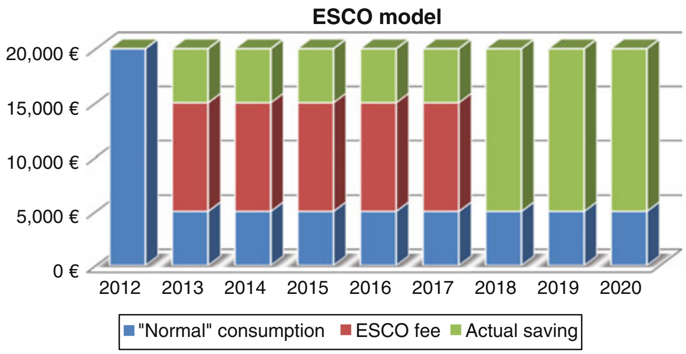

Fig. 1 Illustration of the energy cost savings using the ESCO model. *Source* Prepared in-house

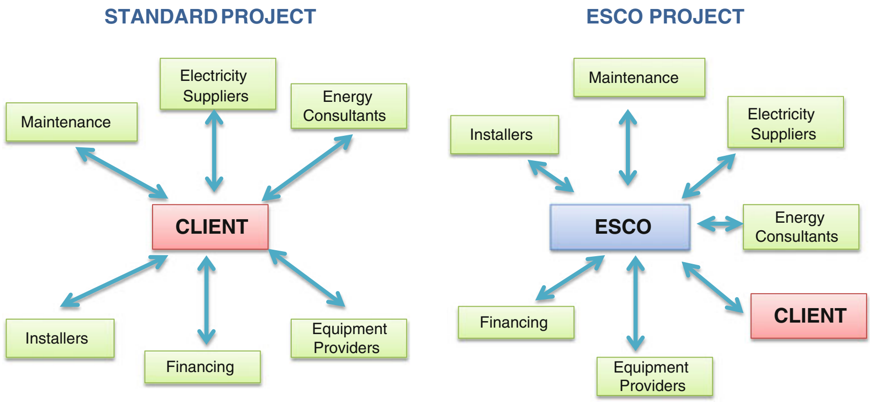

Fig. 2 ESCO interactions with necessary players. *Source* Prepared in-house

2.1 Technological Areas in Which the Model Can Be Applied

The application of the ESCO model is generally limited to the installation, renovation, implementation and/or maintenance of the following technologies: lighting, energy management devices and software, solar thermal for hot water and space heating, combined heat and power appliances, insulation, HVAC, cooking and refrigeration appliances and product manufacturing equipment [5]. ESCO projects vary in complexity depending on the characteristics of the technologies being used, the combination of technologies installed and the related regulations that need to be complied with in order to install each technology. Another important factor that determines the overall risk, and therefore economic viability, of an ESCO project is the degree to which future savings can be guaranteed. For instance, installing LED bulbs is considered "low-hanging fruit" for ESCOs because the savings are easily calculated and the regulatory procedures necessary for the project are minimal. On the other hand, HVAC replacements involve more complex permits and savings calculations, which may increase the perceived risk of the customer as well as that of the ESCO.

2.2 Drivers of the ESCO Industry

There are many conditions that have collaborated to the birth and continuous rise of the ESCO market. Over the next several years, the global ESCO industry is expected to maintain or exceed its current growth trajectory due to factors such as: (a) rising energy prices, (b) concerns surrounding increasing greenhouse gas emissions and climate change, and (c) challenges in obtaining sites and permits for new power plants and major transmission facilities [11]. As it can be seen, the main driving forces of these companies are not only "green" or environment related; they also have to do with economic and legal factors. Therefore, energy efficiency is also considered strategic for the future economic wellbeing of EU member states.

3 The Spanish ESCO Industry

While ESCOs have been operational on a large scale since the early 1990s, the energy service market in the European Union is far from utilizing its full potential, even in countries with a particularly developed ESCO sector. In the case of Spain, the ESCO model could act as an important means to reduce the country's high dependence on foreign oil and natural gas. For instance, in 2010 domestic energy production accounted for only 25 % of the energy consumed, compared to the EU average of 47.2 % [17].

It is practically impossible to reliably estimate the number of players and the total size of the European ESCO market, mainly because the national markets are still rather individual and present particular characteristics. In Spain, there exists no official register of ESCOs, but according to a survey conducted by the European Commission Joint Research Centre Institute for Energy [7], the estimation is that around 15 companies are now operating in this field. The Institute of Energy Diversification and Savings (IDAE), the official state organization that makes decisions regarding energy-related projects in Spain, maintains an unofficial directory of 653 companies operating in Spain (309 in Catalonia) that categorize themselves as ESCOs [13]. Taking into account the significant difference between the estimates of these two organizations and considering the answers of our interview respondents, there is a clear need for an ESCO certification scheme and official directory. This confusion is detrimental to the generation of standardized offerings and an overall atmosphere of trust that is necessary for the widespread adoption of ESCO services in Spain.

According to the Building Performance Institute of Europe [6], large companies dominate the Spanish market, mainly because they have the financial capacity to assume the investment and returns in the long term. In 2007, this market was valued at over 100 million Euros. However in 2010, private companies estimated that the potential market for the national ESCO industry could be valued at €1.4–4 billion. This potential is large enough to attract foreign experienced firms which have been emerging throughout Spain in recent years. Among the national firms, there is a mix of large utilities, construction and multi-services companies and small and medium-sized companies. Most of them are oriented to the energy services sector as a way to diversify their activity. They are mainly operating in public buildings, cogeneration, district heating and street lighting [7].

Over the past few years, significant amount of publicity has been given to the ESCO model in Spain. It is praised on a daily basis on a number of internet media sites and is often a central topic at trade fairs related to construction and energy efficiency. This praise is most likely a result of the sharp decline in the national construction market, recent credit and public budget restrictions and increasing energy costs. In order to stay afloat, many established construction and maintenance companies have begun to diversify by offering ESCO services for renovation projects. Moreover, a number of young energy management companies have sprouted up, offering fully-integrated energy management services to private companies and public administrations. For instance, a growing number of Spanish cities and towns have contracted ESCOs to replace traditional incandescent street lighting with energy efficient LEDs, which have short payback periods and save considerable amounts of scarce public resources. Finally, the increase in energy costs in Spain is forcing consumers to make energy conservation and efficiency a priority. Although the ESCO model is a proven vehicle with which to unlock the country's enormous energy savings potential, it is still new and widely unknown among Spanish citizens.

3.1 Public Support for Energy Conservation and Efficiency Programs

Starting in 2004, the Spanish government implemented various programs, most notably the E4 program (National Energy Efficiency Strategy) and Plan 2000 ESCO, in efforts to promote demand-side measures in the following sectors: buildings, industry, transport, agriculture, public services and appliances. This program supported the implementation of energy audits by subsidizing 75 % of the cost. Depending on the solutions proposed as a result of these audits, a subsidy was given in order to help finance the execution of the suggested actions. Also, the wind and solar industries were highly stimulated by generous feed-in-tariffs. However, given the current economic environment, the government has been forced to change its priorities. As a result, IDAE is expecting a drastic drop in money from the state, reduced from 61.4 million Euros in 2011 to 5.4 million Euros in 2012, as a result of proposed budget cuts.

Another budget-related issue is the expected reduction in the financial support electric companies are required to contribute to programs under IDAE's *Strategic Plan for Energy Efficiency*. These contributions constitute the main financial support for a number of programs designed to improve and promote energy saving technologies. Thus, many planned energy efficiency programs are now paralyzed. Although each autonomous region has their own energy strategies, this constant decrease in state support for energy efficiency projects is considered a major barrier to the development of the ESCO market in Spain.

3.2 Spanish Legislation

The principal EU legislation related to ESCOs is the *Directive 2006/32/EC on energy end-use efficiency and energy services*. The directive stresses the importance of managing end-user demand for energy and the need to improve the security of the member states' energy supplies through energy efficiency upgrades and increased generation from renewable sources. The directive also serves as a roadmap to reach international greenhouse gas emissions reductions targets that need to be attained in order to avoid disastrous impacts due to climate change. Additionally, the directive points out that, by supporting the development of energy efficient technologies, the European Community will become more innovative and competitive on the global stage. Our analysis focuses on the measures relating to increasing the availability and demand for energy services.

Each member state is responsible for enacting the appropriate legislation to carry out the objectives of the directive. The primary piece of legislation designed to achieve these objectives in Spain is the "Sustainable Economy Law", *Royal Decree Law 6/2010* [23]. The law has a specific section dedicated to the promotion of the ESCO market, which outlines measures consistent with the aforementioned EU directive. Unfortunately, as can be seen in the following summary table, interview respondents from both public and private entities recognize that the Spanish authorities have been ineffective in carrying out the European Commission's suggestions (Table 1).

The insufficient compliance of these framework measures to establish a healthy ESCO market mainly stems from the negative impacts of the financial crisis which have drastically restricted public budgets and redirected resources. Notwithstanding, the majority of respondents believe that an adequate framework could be in place if only the state would carry out the currently established Royal Decree laws.

Table 1 Summary of Spain's compliance with ESCO-related legislation

EU Directive 2006/32/EC recommendations for ESCO market development	Level of compliance in Spain
Establish funds to subsidize ECE programs and promote the development of a market for energy services (including start-up funding)	Insufficient
Exchange of information and best practices with other member states	Insufficient
Ensure the availability of high-quality energy audits	Insufficient
Stimulate the use of third-party financing arrangements	Insufficient
Ensure availability of qualification, accreditation and certification schemes for providers of energy services and energy audits	Insufficient
Ensure a level playing field for market actors (other than energy distributors, distribution system operators and retail energy sales companies), such as ESCOs, to independently offer and implement energy services, energy audits and energy efficiency improvements	Insufficient
Repeal or amend legislation that restricts the use of financial instruments for energy savings projects	Insufficient

Source Prepared in-house based on EU Directive 2006/32/EC, Royal Decree Law 6/2010 and interview responses

3.3 Barriers to the ESCO Industry in Spain

In addition to the hurdles caused by the Spanish government's inability to comply with EU and Spanish legislation, we have identified a number of additional barriers to the development of the ESCO market in Spain, which we have grouped into the following five categories:

- **Administrative**: Overall, local governments in Spain are composed of inefficient decision-making structures that are extremely difficult to change; the public procurement process is lengthy and inefficient and; administrative accounting systems are not set up to efficiently realize energy cost savings.
- **Technical:** There are no standard and enforced measurement and verification protocols and; there lacks a neutral third-party institution that certifies the accountability of a particular ESCO.
- **Financial:** There are no suitable financing schemes for the development of ESCOs and ESCO projects. Before the economic crisis, most ESCOs dealt with commercial banks for financing. However, now this source of financing has virtually disappeared. Currently, many ESCOs are financing projects with their own money which is unsustainable. High transaction costs decrease interest for both the client and the ESCO. ESCOs cannot justify the administrative costs to carry out small projects.
- **Informational:** Citizens have limited awareness of energy efficient technologies; high perceived technical and financial risk and aversion to long payback periods. Split incentives: a renter pays the energy bill while the owner is responsible for any renovations. Thus, the owner has no incentive to invest in energy efficiency measures since the savings are captured by the renter. Likewise, the renter is not sure if she will live in the property long enough to recuperate such an investment.
- **Market-related:** Each autonomous community has their own legislation and hierarchy related to energy generation and conservation. This represents an obstacle for ESCOs to expand into several regions and therefore reach a critical mass and obtain operational efficiencies.

Considering the reality that Spain is highly fragmented with respect to the particular energy policies and cultural environment found in each autonomous region, we became motivated to carry out an analysis of the ESCO market at the Barcelona metropolitan level.

4 The Barcelonian Framework

Barcelona is less pollutant compared to other globally important cities in a number of metrics, such as greenhouse gas emissions per inhabitant. For instance, in 2008, greenhouse gas emissions per capita in Barcelona were roughly half of those in

London [4]. Even so, the government of Catalonia and the city of Barcelona are continuing to make great strides to maintain Barcelona as a clean and more energy efficient city.

The principal platform designed to achieve these goals is the Institut Català d'Energia (ICAEN) [12]. Its main functions are comprised of providing information about the Catalan energy sector, educational content regarding energy conservation and efficiency, financial aid for specific technology renovations, implementing relevant legislation, energy market statistics and targeted reports. With respect to ESCOs, they are trying to standardize the legal aspects of an ESCO project by providing model contracts and clauses.

Dialogue between ICAEN, as well as other governmental entities, and private ESCOs is facilitated by the recently formed Clúster d'Eficiencia Energética de Catalunya (CEEC). They also strive to engage the entire value chain, eliminate barriers to the ESCO market to increase investor confidence, negotiate with banks to create new financing options for ESCOs and provide support for EU R&D project applications. Currently, their main aim is to define projects according to their size and inherent characteristics in order to allow for ESCOs to specialize by project type. This will serve as a means to guarantee the quality and results of a venture.

With respect to local policy instruments to foster the adoption of energy efficiency products and services, the city of Barcelona appears to be quite proactive. The recently published *Plan for Energy, Climate Change and Air Quality 2011–2020* (*PECQ*) provides a comprehensive analysis of the city's energy consumption strengths and weaknesses as well as a clear roadmap for reaching new objectives.

4.1 The Solar Thermal Ordinance

One of the aims of the *PECQ* is to take advantage of Barcelona's primary source of renewable energy: sunshine. The *Solar Thermal Ordinance* (STO), put into effect in 2000, requires all new construction and renovations to supply 60 % of the building's sanitary hot water via solar thermal (ST) roof installations.

However, as with any new policy instrument, there are some gaps to be filled. The person responsible for solar energy projects at the Barcelona Energy Agency stated that due to underperformance, many installations only generate 30–40 % of a building's sanitary hot water supply. This is the result of a moral hazard issue. The STO states that "the application of this ordinance will be done in each case depending on the best technology available." However, construction companies often use inferior materials in order to minimize the cost of installing a ST unit. Furthermore, in the rare event that the city decides to perform an inspection of a ST unit, the company knows that a fine will not be imposed. The same moral hazard situation exists for maintenance companies hired for the ongoing operation of an installation.

The *PECQ* does not directly address these weaknesses in the STO, but suggests the need to update the ordinance to exploit the immense rooftop area, over 109 million square meters (in 2006), of the existing buildings by encouraging the installation both ST as well as PV units. It was expressed that the use of ESCOs to install ST units on existing multi-tenant apartment buildings was explored, but the small scale of the individual installations is apparently not financially attractive to ESCOs. However, as ST and PV technologies become more mature, prices will decrease and allow for shorter payback periods. This will help to decrease perceived risk, both for the installer and the homeowners' association. Additionally, a more innovative ESCO contract could be devised by finding a way to pool together various installations of different homeowners' associations in order to reach a desired profitability threshold. In any case, it is clear that Barcelona's new solar policy should provide a favorable framework for the incorporation of ESCOs in order to maximize the benefits for citizens and local businesses.

4.2 Use of the ESCO Model in the Renovation of Public Buildings

The relevant legislation points out that public administration should be lead-user of the ESCO model to carry out measures for improving energy efficiency. They are required to communicate their actions and results to citizens and/or companies in order to encourage the widespread use of the model. The public entity responsible for energy efficiency and conservation projects in government buildings is the Barcelona Energy Agency (AEB in Catalonian). They have attempted to contract ESCOs to carry out renovations, but unfortunately, aside from a few education centers, the Liceu theatre renovation is the only exemplary ESCO project in Barcelonian public buildings. According to the AEB representatives interviewed, the absence of more examples of ESCO projects in the public sector is due to factors of the following nature:

- **Administrative:** In order to make the necessary payments to the ESCO, the AEB must deal with two independently managed municipal accounts: the "investment account" and the "maintenance account". The payments would be made by the investment account yet the energy costs savings would be captured by the maintenance account. This condition causes a split incentives issue, which prevents projects from going forward. The recently changed law dictating public procurement rules creates two main problems for ESCO projects. Firstly, the bidding process is now so long that it creates unusually high transaction costs for the ESCOs involved. Furthermore, the legal framework allows for collusion among bidders. For instance, bidding ESCOs enter in a quid pro quo situation by "exchanging" public projects. After winning the initial round, the selected companies enter into a "competitive dialog." If their conditions are not met, then neither of them follows through. For this reason, many projects are left abandoned.

- **Technical:** In general, ESCOs that have participated in the bidding process do not use a unified protocol to measure and verify energy savings. This makes it very difficult for the AEB to compare bids.
- **Financial:** Many of Barcelona's public buildings are old and need an integrated reformation to become energy efficient, which requires a large investment. Given the current economic situation and the lack of financing sources, not many ESCOs can carry out such a large project.
- **Informational:** Diagnostic energy audits are performed by the AEB and then presented to interested ESCOs. Unfortunately, many times the companies claim that the audit results are not accurate since they do not allow for the desired profit margin. This adverse selection problem prevents many projects from moving forward.

To overcome some of these barriers, the AEB is taking certain actions. For example, the energy consumption of sixty (out of the approximately 2000) public buildings in Barcelona is currently being monitored through a generic, real-time software platform. The objective is to gather accurate data in order to calculate the energy consumption baseline for each building, thereby correcting the asymmetric information problem mentioned above. The agency plans to extend the use of this software to more buildings in different districts. As a solution for the administrative problem, the AEB noted that the Consortium for Education of Barcelona provides a decentralized management which allows education centers more budgetary autonomy. This has enabled a number of centers to carry out ESCO projects. The AEB suggested that this model be replicated for other types of public facilities in order to increase the number of ESCO projects throughout the municipal building portfolio [3].

4.3 A Case Study: Using the ESCO Model in the Private Arena

Sol Solar is a Barcelona-based company that designs and installs ST units. The company recently acted as an ESCO to develop and implement a ST project, consisting of 64.64 m^2 of solar thermal panels, a 1,500 l cistern and a monitoring system, for a 30 year-old multi-tenant apartment building in the city of Barcelona. The objective was to reduce by 50–60 % the building's natural gas consumption used for the supply of sanitary hot water. The contract stipulates that Sol Solar is responsible for the installation and maintenance for a period of 6 years as well as guaranteeing the stated reduction. The form of payment to the company is strictly based on the amount of natural gas saved as compared to a 2-year baseline level of consumption.

Sol Solar states that, acting as an ESCO, they face many of the barriers previously described in this analysis, notably informational barriers represented by the influence of bad references related to unsuccessful installations and the lack of confidence in the way the amortization and savings are calculated. To help overcome these barriers, to ensure the viability of the project and to allow for a contract that would be easy for the customer to understand, Sol Solar targeted buildings with certain consumption characteristics. Specifically, the technical feature essential for the successful implementation of the project was the existence of a centralized water heating system. The original agreement was that Sol Solar would cover 100 % of the cost of the installation, with ICAEN agreeing to reimburse 30 % and the City Council of Barcelona another 15 %. However, due to the fact that this was the first project of its kind in the city, the municipal legislation did not stipulate a viable formula to deliver the payment to the involved ESCO and in the end, a negative response was given. Therefore, the homeowners' association agreed to be responsible for the uncovered 15 % of the installation costs. Additionally, during the 6-year contract period, the homeowners' association pays the calculated monthly baseline amount; the actual consumption is paid to the natural gas company while the difference between the actual consumption and the baseline is paid to Sol Solar. It is also interesting to note that besides the kWh saved, Sol Solar's monthly invoice informs the customer about the number of kilograms of CO_2 avoided and the m^3 of natural gas that do not need to be imported. Once a year, any deviations from the calculated consumption are resolved. When the contract terminates, ownership of the installation is turned over to the homeowners' association, at which point they will only pay for their actual consumption (roughly 50–60 % less than the baseline consumption). If desired, Sol Solar shall offer a maintenance contract to ensure that the installation continues performing optimally in return for 10 % of the yearly natural gas savings.

During the first 3 months of operation, the installation has saved the equivalent of 30,000 kWh, representing a 32 % savings compared to the historical consumption during the same period. According to the president of the homeowners' association, the results have been consistent and highly satisfactory in the first 8 months of operation. As a consequence, these significant savings have reversed the initial skepticism expressed by some neighbors. With regards to the expected barrier created by unfamiliar contract conditions and payback period calculations, our interviewee expressed that no difficulties were encountered. The only unforeseen issue was the necessary reinforcement of the roof in order to support the weight of the solar panels, which was a minor inconvenience. Worth mentioning is the fact that the project's success has attracted international attention and has been visited by a commission interested in replicating it in the Italian residential sector (Table 2).

This demonstrates that existing ST technology is sufficiently mature and reliable to be financed via the ESCO model. However, our case analysis concludes that, in

Table 2 Performance of the ST technology utilized in the Sol Solar residential project

Yearly ST panel efficiency	1,250 kWh/m^2 (capturing 70 % of Barcelona's solar energy)
Yearly energy savings	150,000–180,000 kWh
Yearly emissions reduction	31,500 kg to 37,800 CO_2 kg
Yearly fuel imports avoided	12,766–15,320 reduction m^3 of natural gas
Estimated payback period	6 years

Barcelona, it has only been adopted by very few "innovators". The Sol Solar example shows how an established local policy framework mechanism inspired a ST company to experiment using the ESCO model in an untapped market. The diffusion of this technology, as well as solar photovoltaic, throughout Barcelona's residential buildings depends on the proper implementation of the soon-to-be extended STO. It is expected to provide the adequate mechanisms to foster the installation of both types of solar technologies on the roofs of existing buildings. We suggest that the updated version of the STO provide for a special fund to help cover initial installation costs in order to reduce the risk that most small ESCOs face when taking on a project and help to kick-start the market. Then, as solar technology prices fall and citizen awareness is generated, this fund should be gradually phased out to allow the market to become self-sustaining. Providing loan guarantees may also be an effective way to reduce financial risk for ESCOs.

5 Conclusions

This chapter introduces the ESCO model as an instrument to overcome the "energy efficiency gap," and analyzes the case study of Barcelona, both from the public and private perspectives. The aim is to provide, based on the analysis of the international and national experience, what are the recommendable instruments for the further development of the ESCO market in Spain.

Our analysis has identified weaknesses in the ESCO ecosystem of the following nature: Administrative, Technical, Financial, Informational and Market-related. Thus, our conclusions will be organized into these categories.

5.1 Administrative

Our interviews with the actors involved in the Barcelona ESCO ecosystem have confirmed that there are fundamental limitations resulting from inefficient administrative structures, both at the city and national levels. First, procurement processes are too long and not designed to incorporate the distinctive characteristics of the ESCO model. This produces high transaction costs for ESCOs. Furthermore, based on recent attempts to carry out ESCO projects, Barcelona's public bidding procedure has been unable to prevent collusion among bidders, leaving many projects abandoned. Another major administrative issue is the fact that the current city hall accounting system does not allow for the energy cost savings to be captured by the fund that pays for the renovation.

We find it very necessary for the Spanish government to eliminate the present barriers to the development of the ESCO market. In that respect, local city council/Provincial governments may be more agile than the Spanish government to overcome these barriers as they have a much better understanding of the local conditions. In addition, the full-scale implementation of a mechanism to certify buildings based on their energy efficiency is an essential starting point for gathering information in order to develop adequate policies.

Making fundamental and innovative changes to administrative structures is highly complex and involves the participation of many members of government. However, in our opinion, two types of reforms should be made to the current contracting law to be able to carry out ESCO projects: shorten the length of the public procurement process and adapt the conditions to the distinctive characteristics of the ESCO model.

5.2 Technical

To ensure promised energy savings have been achieved over the contract duration, there exists an internationally accepted procedure called the International Performance Measurement and Verification Protocol (IPMVP). The appropriate policy reforms should be made to make this protocol mandatory in Barcelona in order to assure customers that guaranteed savings have actually been delivered despite changes to variables related to climate, the building and its use over time.

5.3 Financial

Sol Solar's case is just one demonstration of how new energy-saving technologies have been improving their performance, and therefore they provide a reasonable payback period with a continuously decreasing risk for investors.

Currently, the lack of adequate financing schemes for energy saving projects prevents small and medium-sized ESCOs from taking on large renovations. This is a major factor inhibiting the further development of Barcelona's ESCO market. Currently however, due to the economic crisis, commercial financial institutions are more interested in the "low hanging", easy projects, thus limiting activity with longer projects and in some client segments (for instance in the residential sector). Therefore, cash-flow based financing would be the appropriate solution for ESCO projects, where the bank would accept the stream of revenue coming from energy cost savings as collateral.

5.4 Informational

We have found that, in addition to true ESCOs, there are many companies that claim to be ESCOs but are not compensated in function of the energy cost savings generated by a renovation. We suspect that the local ESCO ecosystem could benefit from an official certification scheme specially designed for these companies. ESCOs could specialize in servicing customers with specific consumption profiles (schools, sports centers, supermarkets, etc.), generating higher quality services and minimizing skepticism of potential clients.

In addition, most of our interview respondents expressed that the lack of reliable data related to the building sector is one of the main obstacles for successful implementation of energy efficiency policies. The implementation of a professional and accountable energy audit scheme is recommendable in order to gather reliable information regarding the energy consumption profile of each building. This information would be helpful to establish an adequate work plan for future renovations.

Furthermore, the AEB's buildings monitoring program should be extended to the rest of Barcelona's public buildings and eventually to residential and industrial buildings. This would reduce the existing asymmetric information problem between the AEB and the bidder companies with regards to the audit results.

With respect to another identified asymmetric information problem, we believe that the incorporation of an ESCO contract into the new version of the STO could prove to be an effective solution for overcoming the above mentioned moral hazard issue. By forcing the construction or maintenance company to receive compensation strictly based on the amount of energy savings that are generated by the unit, the company would be incentivized to use the most effective materials to install the unit in order to ensure high efficiency, and thus, a quicker payback period.

5.5 Market-Related

On a national level, efforts should be made to unify the differing regional regulations relating to ESCOs. This would create conditions for a bigger and more attractive market, allowing for a critical mass to be reached. More competition will also lead to better quality energy services and lower prices for consumers. Additionally, a bigger, more competitive market would help Spain become more energy efficient, less contaminant and more energy independent.

In conclusion, we hope that the findings presented in this chapter have contributed to uncover the fundamental obstacles to the widespread implementation of the ESCO model in Barcelona, as well as throughout the rest of Spain. Some of the identified barriers are simply due to incomplete or inaccurate information while others are directly linked to bureaucracy and the insufficient implementation of government policies and procedures. Indeed, given the slow evolution of policy framework conditions, perhaps a deeper investigation into the role of financing institutions as an enabler of innovative business models in the energy efficiency space is warranted.

Appendix

The following respondents have been interviewed and/or responded to personal emails during the period February 2012–June 2012 (Table A.1).

Table A.1 Interview respondents

Name	Organization	Function	Date
Marcos Morras	Efficient Home Energy	Key Account Manager	20/03/2012
Javier Boguña	Sol Solar	Owner	03/04/2012
David Martín	Balantia	Project Manager	20/04/2012
Davide Cannarozzi	Enertika	Finance Director	02/05/2012
Fermín Jiménez	Agència d'Energia de Barcelona	Project Manager of the Solar Energy Department	12/03/2012
Emma Santacana	Agència d'Energia de Barcelona	Environmental and Urban Housing Services	31/05/2012
Luis Miguel Barrientos	Ameresco Servicios Energéticos	Director of Business Development	16/05/2012
Jaume Enciso	Ajuntament de Sabadell	Director of the Servei de Sostenibilitat I Gestió d'Ecosistemes	23/02/2012
Mr. Franques	Homeowners' Association of Sol Solar case	President	24/05/2012
Núria Cardellach	Clúster d'Eficiència Energètica de Catalunya	Manager	11/06/2012

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Policy Inducement Effects in Energy Efficiency Technologies. An Empirical Analysis of the Residential Sector

Valeria Costantini, Francesco Crespi, Gianluca Orsatti and Alessandro Palma

Abstract Energy efficiency technologies represent a key driver for the reduction of energy demand, leading to environmental and economic benefits. This aspect appears to be particularly relevant in the residential sector, where the demand for energy has not shown a decreasing trend over the last two decades. Our study provides a wide-ranging empirical analysis of the drivers of innovation in energy efficiency technologies by looking at the residential sector for a comprehensive panel of 23 OECD countries over the 1990–2010 period. It confirms the importance of adopting a systemic perspective when examining eco-innovation. In particular, the innovation system at both national and sectoral levels, together with the environmental and the energy systems, is found to have encouraged the propensity to innovate and significantly shaped the rate and direction of technical change in the residential sector. A general policy inducement effect is found to be relevant, but the size of its contribution for new energy efficient technologies changes if disaggregated policy instruments are factored in. We note a positive and significant impact driven not only by standard regulations but also by policies aimed at improving the level of consumer information and awareness. This evidence has noteworthy policy implications and suggests paths for the further development of research in this field.

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1 Introduction

Energy efficiency (EE) is one of the most effective means of achieving several goals, such as increasing energy security, fostering international cost competitiveness and reducing polluting emissions. In particular, achieving a more secure, sustainable and affordable energy system is a key challenge for future world development [18, 32, 33]. In this context, the availability and adoption of new energy-efficient technologies are a key driver for reducing overall energy demand as it influences the levels of EE. This aspect appears to be particularly relevant in the residential sector, where the demand for energy to power domestic appliances and equipment shows no sign of slowing but rather a trend of continuous growth over the last 20 years.

Understanding the determinants of the pace of inventions in this sector therefore appears to be an important step for the design of policies for fostering the generation and dissemination of environmental technologies aimed at increasing EE. However, the residential sector is a complex system in which several energy services are used, such as space heating, cooling systems, water heating systems, lighting and several electrical appliances. This implies that major research efforts are needed to properly map the evolution of technologies in this sector and to systematically collect information for specific policy strategies.

Given the limited number of studies that have analysed the drivers of innovation in this field, we propose a comprehensive analysis of the factors affecting the dynamics of EE technologies in the residential sector, with specific attention to the role played by public policies. In so doing, we seek to contribute to the relevant literature: (i) by including in the analysis the domain of electrical appliances which—although relatively unexplored—account for a large proportion of residential energy consumption in view of the great potential that comes with the multiplicative effect of each single appliance; (ii) by analysing the impact of the full array of policy instruments that are assumed to influence innovation activities; and (iii) by extending the country coverage of the empirical analysis to a large number of high-income OECD countries.

The rest of the paper is organised as follows. Section 2 shows the consumption patterns and the innovation dynamics in EE in the residential sector, to provide a better understanding of the energy-growth decoupling process that has occurred in most of OECD countries. Section 3 describes the data used for the econometric analysis, with a particular focus on policies, and Sect. 4 sets out the empirical strategy and presents the results of the model. Section 5 concludes with some policy implications and further research lines.

2 Consumption Patterns and Innovation Dynamics in Energy Efficiency for the Residential Sector

2.1 Energy Consumption Trends and Energy-Growth Decoupling

In the decades following the first oil shock energy consumption trends have changed substantially, due to several changes in energy policy and in consumption behaviour, especially in the developed world. Decreases in energy and carbon intensity can be detected in almost all sectors of the economy, and most strongly in the manufacturing industries. A look at the last two decades (1990–2010) reveals that there are some divergences, especially when the residential sector is considered. A comparison of indices taking 1990 as base year, using the ratio of total energy consumption to Gross Domestic Product (GDP) for selected OECD countries (Fig. 1) reveals that the average trend for OECD countries and the path for three major energy consumers (Germany, Japan and the US) are continuously decreasing over time, with the exception of Japan up to 2004. The residential sector shows, on average, similar dynamics for OECD economies, with increasing values for Japan and a less evident negative trend for Germany (Fig. 2). Index numbers based on the ratio of energy consumption in the residential sector to final household consumption expenditure reveal interesting differences from the previous overall trend, with the divergence between Japan and the rest of OECD countries appearing to be much wider.

This evidence provides an initial broad picture of cross-country specific features, indicating that some countries have made less effort to improve EE in the residential sector than in other sectors, while other countries have obtained particularly strong EE gains in this sector. There may be several reasons for these divergences.

An initial explanation is provided by different levels of stringency in residential sector EE policies adopted in OECD countries during the study period. Indeed, the number of policies increases substantially after the year 2000 (see Sect. 3), with

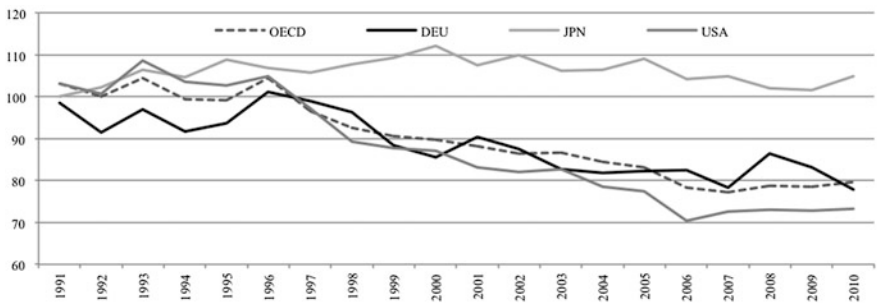


Fig. 1 Energy intensity trends in the total economy, 1990–2010 (1990 = 100). *Source* own work based on IEA [34], World Bank [79]

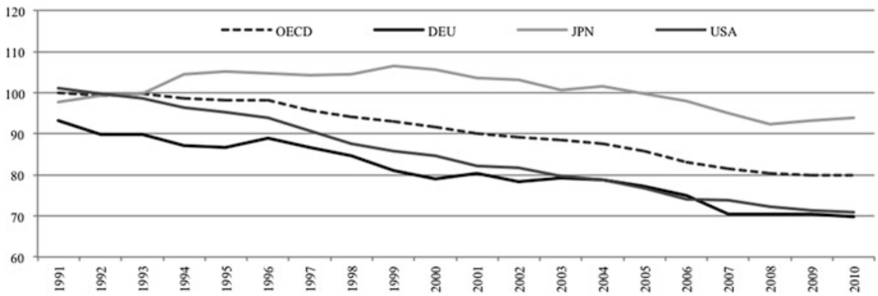


Fig. 2 Energy intensity trends in the residential sector 1990–2010 (1990 = 100). *Source* own work based on IEA [34], World Bank [79]

countries such as Japan, the United Kingdom and the US adopting more stringent, more pervasive policies only recently, while others such as Denmark, Finland and Germany have introduced a relatively smaller number of policies, but adopted them in the early 1990s. It is also worth noting that the effectiveness of environmental policies is closely related to the instruments adopted. Several differences arise when comparing for instance command and control with market-based instruments [6], with the latter being considered as cost effective as well as more suitable for pushing technological change [71].

As a matter of fact, this field of analysis requires a complex framework, where several driving factors may help to explain divergent performance trends, such as institutional and technological capabilities, as well as the more general innovation system at country level. It is also true that gains in resource efficiency must be strictly related to technological innovation, encouraging a large number of scientific contributions in an attempt to disentangle this issue.

2.2 Eco-innovation and Energy Efficiency

Broadly speaking, reduction of the overall residential energy demand can be thought of as a function of the level of EE, which in turns depends on the availability and adoption of new EE technologies such as intelligent building design and high-performance buildings including highly efficient heating, ventilation and water heating systems. In this regard the dynamics of the technologies used in the residential sector are a key issue.

Considering the strong linkage between the energy system, the environment and innovation processes, EE can be included in the broader framework of eco-innovation [47, 61]. In this chapter we are particularly interested in understanding how public policies may induce innovation efforts at country level. An examination of the growing literature on different technological environmental domains

[4, 8, 10, 27, 31, 44, 46, 48, 53, 54, 62, 67] suggests that a patent-based analysis may be the most appropriate way to study innovation dynamics in this field, in view of the lack of specific data on efforts in research and development (R&D), especially in the private sector.

Despite some major limitations, the use of patent data is widespread in the literature on the economics of innovation (see [2, 3, 13, 24, 25, 42, 49, 50, 52, 64, 66, 74, 75]). Indeed, patents provide a wealth of public information on the nature of inventions and applicants for rather long time series, indicating not only the countries where inventions are produced but also where new technologies are used and derive from. Patent data frequently represent the direct result of R&D processes, a further step toward the final output of innovation that is useful knowledge through which firms are able to generate new profit sources. Moreover, patent applications are usually filed early [24], hence they can be interpreted not only as a measure of innovative output but also as a proxy for innovation-related activity [68]. Besides this, it is worth noting that patent data are subject to an extensive process of updating of their information content, which is continuously enriched by national and international patent offices. In addition, EE technologies are only partially and roughly represented in the set of international patent classifications.

An initial contribution to fill this gap is provided by Noailly and Batrakova [57], who analyse the building sector for a limited number of countries. They use patent applications per year in selected areas of environmental technologies in buildings, classified by applicant country and priority date. In order to identify the relevant patents, they refer to technical experts, providing IPC classes related to specific technologies together with a list of keywords for describing the state-of-the-art of EE technologies in the building sector. Although this paper provides an important contribution in mapping EE technologies, it does not consider the important domain of domestic electrical appliances, which account for a large proportion of final energy consumption and have a very high potential impact in terms of EE gains thanks to the multiplier effect derived from their widespread distribution [32]. This gap has been partially filled by the recent Cooperative Patent Classification (CPC), a collaboration between the European Patent Office (EPO) and the World Intellectual Property Office (WIPO), which now includes specific patent classes for EE, also including four domestic electrical appliances.[1] In particular, for patents related to buildings, we adopt the methodology based on keywords developed by Noailly and Batrakova [57], extending the search to 23 OECD countries and 21 years. In our paper, we also take into account EE patents for domestic electrical appliances, following the recent paper by Costantini et al. [16], which provides a comprehensive, up-to-date contribution in mapping this technological domain (including also the new EE classes based on the CPC-Y02 classification) while maintaining the same patent search methodology as for the previous sectors. As a result, we obtain a set of 55,261 patent applications related to EE technologies in different residential sectors, using a homogeneous extraction methodology. Once patent data were

[1] In particular, freezers, refrigerators, washing machines and dishwashers.

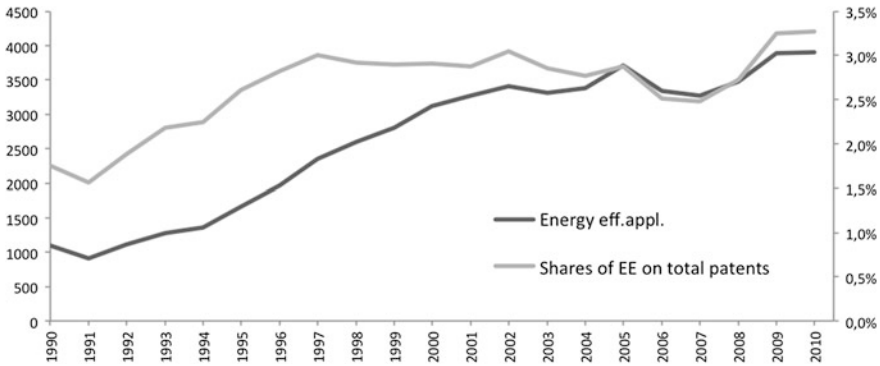


Fig. 3 Trends in EE patents in absolute numbers and as a proportion of total patents at EPO (1990–2010). *Source* own work based on EPO [19]

extracted using the Thomson Reuters Core Patents search engine, the patent count was calculated and sorted by application date,[2] with duplicates being dropped to avoid prevent double counting of patents. Finally, the whole technological domain was divided into three sub-domains: building, lighting and large residential appliances (see Sect. 3). A complete list of keywords is provided in Table 6a, b in the Appendix. For a comprehensive description of the data extraction methodology, see Noailly and Batrakova [57] and Costantini et al. [16].

2.3 Trend in Energy Efficiency Patents

The number of patents for EE residential technologies increased dramatically in the period 1990–2010. Figure 3 depicts the trends of EE patents in the residential sector and the proportion of the total patents registered at EPO that they represent in the same period for the countries listed in Table 7. Despite a slight decrease between 2005 and 2007, which mirrors a general slump in patenting activity, EE patents show constant growth. After 2007, EE patenting activity increased again, more strongly than in the past, most likely due to the increasing application of EE regulations in each country (e.g. the implementation of EE Action Plans, EEAPs, in the European Union).

The growing trend is also confirmed by the sectoral analysis shown in Fig. 4 for the three sub-sectors of EE residential technologies considered, namely buildings, lighting and large electrical appliances. In the case of buildings the increase in patenting activity was particularly strong, especially in the period 2006–2010. It is

[2] Specifically the "early application date" document field. Moreover, only application codes A1 and A2 are considered in order to capture the most innovative inventions.

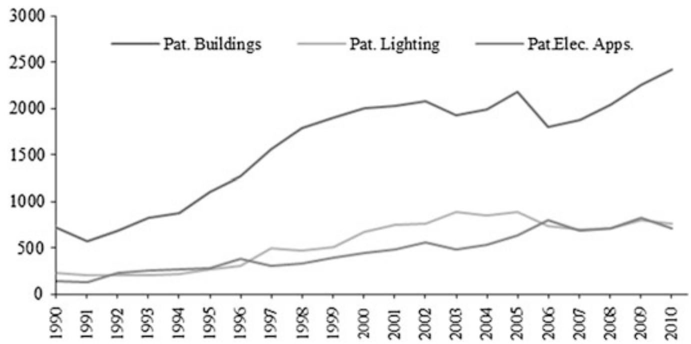


Fig. 4 Trends in EE patents at EPO in the three sub-domains (1990–2010). *Source* own work based on EPO [19]

worth noting that patents for highly efficient appliances are not affected by the general downturn in patenting activity in 2005: they maintained constant growth over the entire period analysed. In terms of sectoral contributions, patents for buildings account for the most EE technologies, followed by lighting and electrical appliances, both of which make moderate contributions to the total number of EE patents filed. Adding up all the patents in the entire period, buildings account for 73 % (33,973 applications), lighting for 21 % (11,699 applications) and electrical appliances for 17 % (9,619 applications).

3 Innovation Drivers in Residential EE Technologies: The Empirical Framework

A large body of literature has sought to identify the main forces pushing and supporting eco-innovation, using both theoretical and empirical models. Such analyses suggest that a systemic approach is an appropriate way to study the determinants of introduction and the patterns of dissemination of eco-innovation [17, 30, 73], as it sheds light on the relevance of both demand-pull and supply-push forces and on the primary role played by public policies in this context [31, 55, 69]. From a general point of view, Coenen and Díaz López [12] clearly emphasise that a systemic approach is necessary in eco-innovation studies whatever theoretical framework is adopted. Regardless of whether technological innovation systems, socio-technical systems or sectoral systems of innovation make up the analytical setting of the analysis, private efforts in innovation, technological and institutional capabilities and different public support policies should be accounted for in an integrated manner.

Building on this comprehensive approach, the empirical analysis proposed seeks to take into account the different forces that shape the rate and direction of eco-innovation in the sector considered. In particular the dependent variable, represented by the count of patent applications at the EPO by 23 countries over the period 1990–2010, is regressed against a set of explanatory variables referring to innovation, market, institutional, energy and environmental systems. The groups of explanatory variables are as follows.

The Innovation System There is a large strand of literature on the role of national and sectoral innovation systems [59]. Recently, the innovation process as a whole has been interpreted as the result of complex relationships between different actors, including not only market players but also private and public institutions, government interventions and intangible elements such as spillover effects and tacit knowledge flows. In this study, we particularly stress the role of public policies in inducing innovation in EE, but other general aspects of the innovation system are also taken into account. First, we test efforts and the capability to innovate at country level—proxying the knowledge stock via national gross expenditure in R&D (GERD), which includes expenditure by business enterprises, higher education institutions, the government and private non-profit organisations (data taken from OECD Main Science and Technology Indicators, [63]). Besides this, sectoral features of the energy-technology system also have to be considered. Indeed, the energy sector is characterised by certain specific aspects that affect the performance of technological improvements such as slow response to stimuli to innovate due to high capital intensity, longevity of capital stock, time needed for learning and experimentation, clustering and spillovers [72, 80]. In the light of this, we also test the sectoral knowledge stock for energy, proxied by specific expenditure in R&D on EE, using data provided provided by the IEA [36].

We assume that technological knowledge operates cumulatively, and can thus be added up over time. On the other hand, knowledge is subject to deterioration as it becomes obsolete [20] and should be discounted to take this effect into account. The literature suggests a knowledge depreciation rate of between 10 and 40 % per annum (see [7, 22, 26, 55]). We have decided to apply a moderate decay rate of 15 %[3] considering the high level of "inertia" that characterises the energy technology system. In order to build up the national and sectoral knowledge stocks, we follow the Perpetual Inventory Method suggested in OECD [60] as follows:

$$\text{Stock}_{\text{R\&D}} = \sum_{s=0}^{t} \left\{ \text{R\&D}_{i,s} \cdot e^{[-\gamma(t-s)]} \right\} \quad (1)$$

where γ indicates the discount rate, i indexes countries and s, t index time. All values, for both GERD and R&D in EE, are converted into constant US dollars at 2010 levels.

The Market System Market effects in spurring innovation have been extensively analysed in economics, dating back to the seminal work by Hicks [29] which gave prices the role of a driving force for more efficient input substitution in which part

[3] As a sensitivity analysis, we also tested different discount rates (specifically 10 and 20 %), but they did not affect our results significantly.

of the process relies on innovation. Here we adopt an extensive interpretation of price-induced effects, extending the framework to government intervention in an attempt to control market prices. Indeed, it is worth noting that although the final substitution stimulus is related to price, the latter can be divided into two components referring to different innovation drivers. The final price influencing the substitution effect often includes government market instruments such as taxes or incentives, which we call the "public" component. Apart from taxes or subsidies, the rest of the price represents the pure market component, which is assumed to be affected only by market forces and not by public intervention.

Many papers have tested the effectiveness of the price-inducement effect (see [9, 67, 76], among the others), and have found prices to play a significant, positive role in inducing input substitution through innovation, particularly over the long run. In the specific sector of EE, few studies have tried to analyse the relationships between prices and EE innovation. Jaffe and Stavins [39] focus their empirical analysis on the adoption of technologies, comparing the effects of energy prices, building codes and adoption subsidies on the average EE level in home construction in the US over the period 1979–1988. They find that energy taxes have a positive but relatively small impact on technology dissemination, but that subsidies have a stronger positive effect. By contrast, building code requirements (a form of direct regulation by technology standards, measured by using dummy variables) are found to have no effect. The paper by Newell et al. [56] is the only one that focuses specifically on home appliances. By evaluating the impact of energy prices and regulatory standards on the introduction of new home appliances (e.g. gas water heaters and air conditioners) in the US between 1958 and 1993, it confirms the price-inducement hypothesis, finding that falling energy prices work against the development of energy-efficient appliances. Noailly [58] is the most recent study, and the only one related to EE innovation measured by patent data. It investigates the impact of alternative environmental policy instruments (regulatory energy standards in building codes, energy prices and specific governmental energy R&D expenditures) on energy-efficient technological innovations in the building sector. The study covers seven European countries over the period 1989–2004 and finds that, for the specific case of the building sector, regulatory standards have a greater impact on innovation than energy prices and R&D support.

In our analysis, the price effect considered is the price-tax bundle calculated as the ratio of the overall cost of energy taxation to the total cost of energy consumption as follows:

$$\text{Price} - \text{tax bundle}_{it} = \frac{\sum_{n=1}^{3}\left(\text{tax}_{n,it}\cdot \text{ener\_cons}_{n,it}\right)}{\sum_{n=1}^{3}\left(\text{price}_{n,it}\cdot \text{ener\_cons}_{n,it}\right)} \qquad (2)$$

where n indexes diesel, electricity and gas. Price and tax rates are taken from IEA Energy Prices and Taxes Statistics [35], while data on energy consumption are taken from IEA Energy Balance Statistics [34]. All data refer strictly to the residential sector.

Table 1 EE residential main target and specific sub-domains

Main target sub-domain	Specific sub-domains
Buildings	Building code
	Building type (residential only)
	Energy class
	Existing buildings
	New buildings
Lighting	Residential
Residential appliances	Computer
	Cooking & laundry
	Home entertainment
	Other
	Refrigeration
	Space cooling
	Space heating
	Standby
	Ventilation
	Water heating

Source IEA [37]

The Institutional System In this empirical framework, we describe the institutional environment in terms of the different public policies implemented at country level for this specific domain (Table 1).

Using policy data, we investigate the hypothesis that although many policy interventions were not initially implemented with the purpose of stimulating new EE technologies, they have all helped to encourage the complex process of innovation, in particular at the invention stage, through an inducement mechanism that we call the "policy-induced effect". Policy data are taken from the IEA's "Energy Efficiency Policy Database" [37], which provides comprehensive, up-to-date information on EE policies in seven demand sectors (buildings, commercial/industrial equipment, energy utilities, industry, lighting, residential appliances and transport) and on policy measures across these sectors in 23 OECD countries.[4]

Public regulations can be considered on the basis of various criteria (e.g. type of measure, target audience, effective enforcement year, jurisdiction, policy status, etc.). National and supranational policies—still in force or ended during the 1990–2010 period—are included in the analysis. In order to exclusively capture residential-related EE policies, public regulations are selected according to the three main residential target audiences offered by the IEA, namely "buildings", "lighting"

[4] http://www.iea.org/policiesandmeasures/energyefficiency/.

and "appliances" (see Table 1). These residential-specific targets are separated from commercial-, industrial- and transportation-oriented policy measures using an ad hoc semantic methodology based on co-word analysis applied to the main description of the policy. Table 2 illustrates the six policy types and their related instruments which constitute public regulations. Each of the six policy types offered by IEA is considered.

At first glance, the trend in EE policies follows that of the patents filed. This similar trend is an important piece of initial empirical evidence and deserves further investigation. OECD policies adopted to improve EE in residential buildings, lighting and electrical appliances have multiplied dramatically over the past decade, and the instruments implemented have become increasingly heterogeneous. According to the IEA [33], new policies were put in place to strengthen building codes for new buildings in Canada, South Korea, Luxembourg, The Netherlands and the United Kingdom during 2011; building certification has also been implemented in EU Member States. Information on EE in existing buildings is systematically collected and reported in Canada, Germany, Japan, South Korea and New Zealand. Minimum Energy Performance requirements (MEPs) have been strengthened and extended to cover new appliances in many OECD countries. New MEPs and labelling for television sets, set-top boxes and digital television adaptors

Table 2 Policy types and instruments

Policy type	Instrument
Economic instruments	Direct investment
	Fiscal/financial incentives
	Market-based instruments
Information and education	Advice/aid in implementation
	Information provision
	Performance label
	Professional training and qualification
Policy support	Institutional creation
	Strategic planning
Regulatory instruments	Auditing
	Codes and standards
	Monitoring
	Obligation schemes
	Other mandatory requirements
Research, development and deployment (RD&D)	Demonstration project research programme
Voluntary approaches	Negotiated agreement (public-private sector)
	Public voluntary schemes
	Unilateral commitments (private sector)

Source IEA [37]

have been introduced in Australia, Canada and Japan, and numerous standby power requirements, planned in 2009, have been fully implemented. Moreover, most OECD countries continue to phase out inefficient incandescent lamps. Canada, Japan, the Netherlands, the United Kingdom and the US have also supported international efforts to stimulate adoption of higher-efficiency alternatives to fuel-based lighting in off-grid communities in developing countries.

Although OECD countries have a strong tradition of promoting EE (dating back to the two oil crises of the 1970s), residential-related EE regulations have been consistently promoted only since the early 1990s. Considering the 23 OECD countries analysed as a whole, 253 different policies can be identified for the 1974–2010 period, 245 of which have been implemented since the 1990s (Fig. 5).

The first major peak in residential-related policy implementation occurred at the turn of the millennium (15 new regulations in 1999 and 18 in 2000), though 2006, with 41, was the year with the most policies implemented. After 2006, government law-making in residential-related EE continued to be significant until 2009, with an average of more than 25 new regulations per year. In 2010, there was a slowdown, with only nine new regulations implemented.

There has been an interesting trend in the policy framework of public regulations in OECD countries over the last two decades. Policy packages have become more heterogeneous, and have shown an increasing level of diversity in terms of both the instruments implemented and the targets at which they have been aimed.

Figure 6 provides a chronology of the introduction of alternative policy types in the OECD countries analysed. Each point in the scatter plot represents the year in which a specific policy type was first introduced in the country indicated. As expected, policy types were first implemented at different times. The countries analysed seem to have preferred first to implement regulatory instruments (e.g. codes and standards, obligation schemes). Then economic instruments (e.g. direct investment, fiscal/financial incentives) and information and education instruments (e.g. performance labelling) are further implemented in the 1990s. Policy support

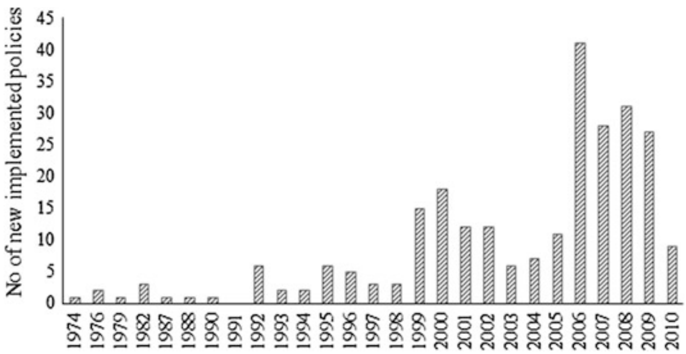


Fig. 5 Overall residential-related EE policies in wealthy OECD countries (1974–2010). *Source* own work based on IEA [37]

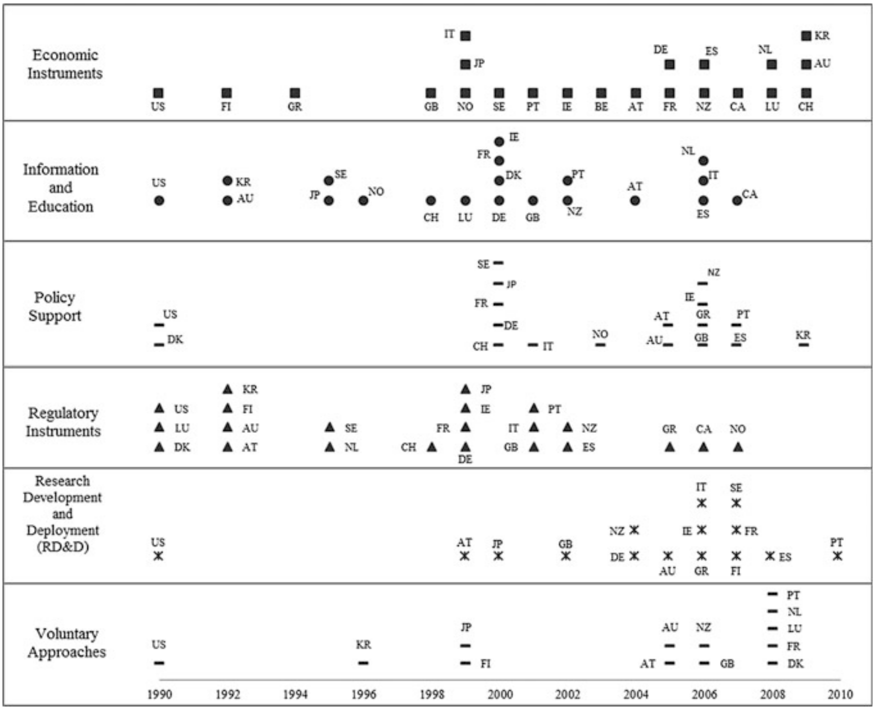
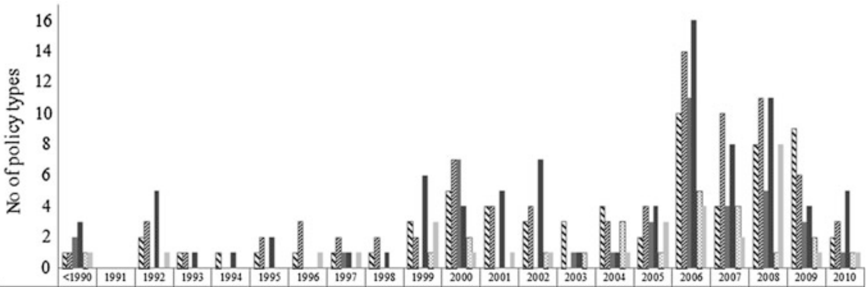


Fig. 6 First implementation of residential-related EE policies in 23 OECD countries by type. *Source* own work based on IEA [37]

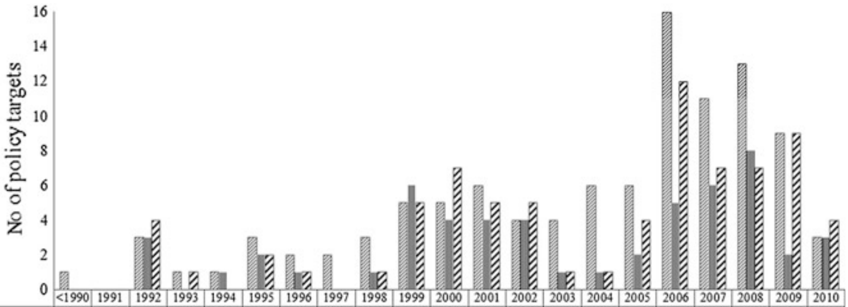
tools, research, development and deployment (RD&D) instruments and voluntary approaches however, with the exception of the US (where they were all implemented in the 1970s) and Denmark (which implemented policy support instruments during the 1980s) were first implemented only during the 2000s. Since the mid-2000s, the entire package of residential-related EE policy types has been in force in most of the countries analysed. As a result, the level of policy heterogeneity has increased significantly.

Figure 7 plots the level of each of the six policy types implemented over the period from 1990 to 2010. Regulatory instruments, information and education and economic instruments are the most widely used policy types. However, the implementation of policy support tools, RD&D instruments and voluntary approaches increases considerably from the mid-2000s onward. As mentioned above, all six policy types have significantly and persistently increased since the mid-2000s and have been implemented simultaneously in almost all the countries analysed. Indeed, the number of multi-instrument policies has recently increased greatly in the OECD area. The same consideration is also evident with respect to residential-related EE targets, which have shown continuous growth and increasing co-occurrence in recent years (see Fig. 8).



	<1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Ec Instr	1	0	2	1	1	1	1	1	1	3	5	4	3	3	4	2	10	4	8	9	2
Info&Edu	1	0	3	1	0	2	3	2	2	2	7	4	4	0	3	4	14	10	11	6	3
Pol Supp	2	0	0	0	0	0	0	1	0	0	7	0	0	1	1	3	11	4	5	3	1
Reg Instr	3	0	5	1	1	2	0	1	1	6	4	5	7	1	1	4	16	8	11	4	5
RD&D	1	0	0	0	0	0	0	0	0	1	2	0	1	1	3	1	5	4	1	2	1
Vol App	1	0	1	0	0	0	1	1	0	3	1	1	1	0	1	3	4	2	8	1	1

Fig. 7 Number of policies by instrument type (1990–2010). *Source* own work based on IEA [37]



	<1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Buildings	1	0	3	1	1	3	2	2	3	5	5	6	4	4	6	6	16	11	13	9	3
Lighting	0	0	3	0	1	2	1	0	1	6	4	4	4	1	1	2	5	6	8	2	3
Appliances	0	0	4	1	0	2	1	0	1	5	7	5	5	1	1	4	12	7	7	9	4

Fig. 8 Number of policy instruments by target sub-domains (1990–2010). *Source* own work based on IEA [37]

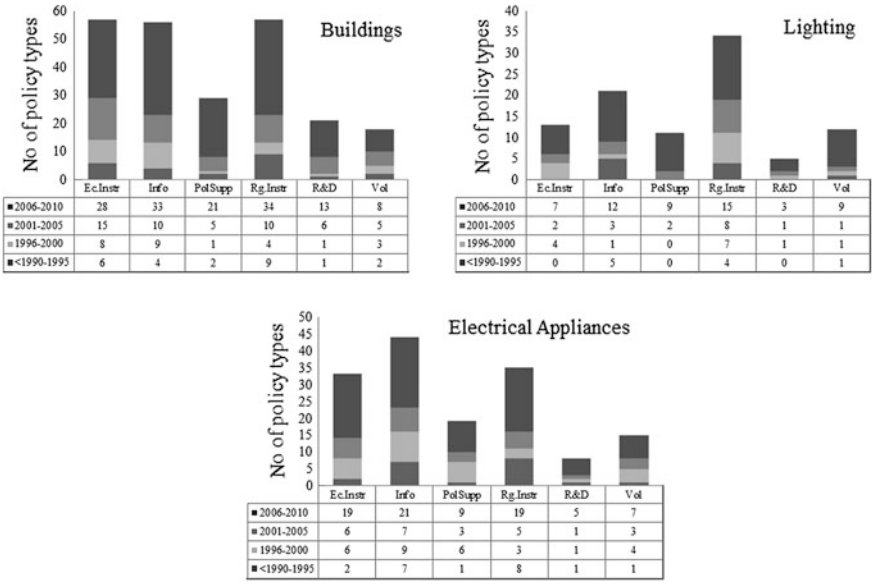
Building-related regulations, the most widely disseminated residential-related policy interventions over the period analysed, are characterised by the large-scale introduction of economic, regulatory and information and education instruments. Notwithstanding, lighting and appliance-related regulations have both more than doubled since 2006. For lighting-related policies, regulatory instruments seem to be preferred, while information and education tools, such as residential performance labelling, are the most widely implemented policy instruments in appliance-related regulations. Nevertheless, as stressed above, there have been dramatic increases in all six policy types in all the policy target areas analysed since the mid-2000s, more and more in co-occurrence with other instruments.

Country-level analysis shows that the EU-15 group of countries have implemented the largest number of residential-related EE public regulations. This is particularly evident since the mid-2000s, with 81 new policies. The crucial years are 2006, 2007 and 2008, with 27, 19 and 19 new policy interventions, respectively. The US maintains a consistently high level of implementation of regulation from the 1970s to the mid-2000s, with major increases in 2008 and 2009. By contrast, implementation of regulations in Japan peaked in the period 1995–2000, slowed down in the early 2000s and picked up again in 2006. As stressed above, these trends are also characterised by significant changes in specific policy mixes. All the countries analysed have shifted over time to higher levels of heterogeneity in their policies, increasingly implementing both multi-target and multi-instrument policies. This is particularly evident for the EU and the US, which employ the highest number of policy instruments in all the policy target areas analysed (see Fig. 9).

In the econometric model we shape the institutional framework by building a discrete variable as the stock of EE policies, calculated as the cumulative number of policy instruments in force at time t in country i, as follows:

$$KPOL_{it} = \sum_{s=1}^{t} POL_{is} \tag{3}$$

dividing by six policy instrument types and three policy sub-domains as specified in Tables 1 and 2. This modelling choice allows us to consider for each year the



Buildings

	Ec.Instr	Info	PolSupp	Rg.Instr	R&D	Vol
2006-2010	28	33	21	34	13	8
2001-2005	15	10	5	10	6	5
1996-2000	8	9	1	4	1	3
<1990-1995	6	4	2	9	1	2

Lighting

	Ec.Instr	Info	PolSupp	Rg.Instr	R&D	Vol
2006-2010	7	12	9	15	3	9
2001-2005	2	3	2	8	1	1
1996-2000	4	1	0	7	1	1
<1990-1995	0	5	0	4	0	1

Electrical Appliances

	Ec.Instr	Info	PolSupp	Rg.Instr	R&D	Vol
2006-2010	19	21	9	19	5	7
2001-2005	6	7	3	5	1	3
1996-2000	6	9	6	3	1	4
<1990-1995	2	7	1	8	1	1

Fig. 9 Country-specific policy activity, per type and target sub-domains (1990–2010). *Source* own work based on IEIEA [37]

whole range of policies still in force at time *t*. This shows not only a single impulse depending on whether or not EE measures are in place, but also a qualification of the strength and complexity of the overall institutional system.

The Energy System EE performance can affect all the components of the energy system, enabling it to become more efficient ([21], among others). Indeed, EE technologies can be found throughout energy technologies, on the both the energy production and consumption sides. Moreover, EE performance can be affected by the characteristics of the energy system itself. For instance, a shortfall in energy generation in a given country might lead to higher levels of generation and adoption of EE technologies to counterbalance the suboptimal supply of energy. In such endogenous mechanisms, the evaluation of the energy system as a whole appears crucial, especially in a panel setting.

A recent study has developed the concept of an "energy-technology innovation system" (ETIS), defined as "the application of a systemic perspective on innovation to energy technologies comprising all aspects of energy systems (supply and demand); all stages of the technology development cycle; and all innovation processes, feedbacks, actors, institutions, and networks" [22], p. 139. Such a system relies on the role of innovation for improving overall EE but is strictly related to specific contexts and incentive structures, which means that the processes and mechanisms at work within the system must be taken into account, including the roles of private actors, networks and institutions.

In the light of this, we identify a set of variables in an attempt to capture some intrinsic characteristics of the energy system of a country, and more precisely the following:

- The level of energy independence. The mechanisms at work here are based on the hypothesis that if a given country is a net energy exporter, then it is most likely rich in energy supplies and less pressed to innovate in EE technologies. In other words, the greater the energy abundance, the lower the stimulus is to make the national energy system more efficient through the adoption and generation of technology.
- The effect of major additional non-coal energy sources such as nuclear power plants. Nuclear energy accounts for a significant proportion of energy production in many countries and an extra source of energy that might contribute to reducing effort in EE gains. Moreover, the presence of nuclear power plants reflects long-term national energy strategies, since their construction implies that a long time is needed to obtain returns on investments. This variable is expected to have a positive impact in countries that have a low level of nuclear power production.
- The level of energy intensity, to check out the overall efficiency of a system, which is also an indicator for evaluating different national energy strategies. According to Patterson [65], there are different indicators for assessing aggregate efficiency in the energy system. We use energy consumption divided by the

level of population, but we are well aware that although this indicator is widely use, it is not exempt from bias.[5]

In the empirical model, we combine the effects of the presence of nuclear power generation with the level of energy intensity by interacting these two variables.

The Environmental System Public intervention to reduce pollution and improve the environment has been thoroughly justified in standard environmental economic theory, which starts by assuming the environment to be a public good and assumes that pollution (e.g. greenhouse gas emissions) represents a negative externality, i.e. a cost not internalised by polluters. Indeed, in the absence of public interventions firms do not pay for polluting and thus produce a cost for society by reducing environmental quality. In such cases government intervention is required to set the optimal level of output by balancing the private cost of production (paid by firms) against the social cost of pollution (paid by the community). A typical intervention for internalising the cost of pollution takes the form of taxation, but the role of innovation is also important in inducing firms to introduce higher efficiency, cleaner inputs into their production processes. This second case is also known as environmental-induced innovation.

There is increasing interest in studying the role of environmental regulation in fostering innovation, and conflicting results are often reported which leave the debate still open at present. One major strand of literature assigns a pivotal role to environmental regulation as a driver of innovation processes and business competitiveness, in the well-known framework of the Porter Hypothesis [70, 71]. This provides further justification for green public interventions. According to Jaffe and Palmer [40], the Porter hypothesis can be seen as having three different versions: the first 'weak' version states that regulation stimulates eco-innovation; the 'narrow' version states that the flexibility of different policy instruments can provide firms with even greater incentives to innovate in green technologies; and finally the 'strong' version states that compliant firms can even benefit from cost-savings and technological leadership deriving from eco-innovation. All three versions have been subject to empirical investigation in the past few decades, and non-univocal results have emerged. For instance, Ambec and Barla [1] demonstrate that the Porter hypothesis only operates in the co-existence of different market imperfections. Lanoie et al. [51] finds inverse proportionality between the degree of compliance by firms and the relative effect of the Porter hypothesis, while Costantini and Mazzanti [15], analysing trade competitiveness in the EU, test both the strong and narrow versions of the Porter hypothesis and find that environmental policies generate greater efficiency in the production process through various complementarity mechanisms.

Considering the presence of environmental policies in the full set of countries analysed, we include a country-specific variable—the level of residential CO_2

[5] For instance, Wilson et al. [77] underline the non-technical nature of this indicator for measuring energy efficiency, while Jenne and Cattel [43] point out the bias due to divergent country-specific sectoral economy mixes.

emissions—as a control variable representing the environmental system which can capture any possible inducement effect due to the stringency of different national environmental regulations. By doing this, we seek to test the potential effects of environmental regulations operating as a mechanism through which cleaner technological change can be induced, which has positive impacts on the countries in which regulations are in force [14]. More precisely, we rely on the hypothesis that the lower the level of CO_2 per capita, the higher the level of technological capabilities is, measured by the patent count. Since this variable measures the final goal of environmental regulations—lower carbon intensity, that is the impact of the overall level of emissions from all sectors in a country weighted by its population—we capture any environmental induced-effect policies. Moreover, due to the generality of this variable, the analysis is also effective in countries where the framework of green regulation is weak but other implicit mechanisms are at work, as for instance in the case of Italy [23]. We use emissions data from IEA CO_2 Emissions from Fuel Combustion Statistics [38], measured in Mt of CO_2.

4 Econometric Strategy and Empirical Results

The use of patent data as a proxy of innovation-related activity means that we have to deal with count variables, i.e. variables with non-negative integer values. In our analysis, the variable under scrutiny is the patent count. Patent data on the EE residential sector are divided into three sub-sectors according to policy data: buildings, lighting and four electrical appliances (refrigerators, freezers, washing machines and dishwashers), respectively. As confirmed by Hausman et al. [28] and Baltagi [5], these data usually show a high degree of skewness with upper tails over dispersion (relatively low medians and high means) and a large proportion of zeros. Such features can reflect observed factors such as the size of firms (larger firms usually file more patents than smaller ones) and unobserved heterogeneity (one firm may patent less than another but produce breakthrough technologies). Empirical literature suggests specific modelling strategies for dealing with patents which can be reduced to two main options: the Poisson Regression Model (PRM) and the Negative Binomial Regression Model (NBRM). When the dependent variable is affected by the presence of many zeros the Zero-Inflated Negative Binomial Model (ZINB) may also be a good modelling strategy (for a comprehensive explanation see [11, 78]. In our dataset, the presence of zeros in the dependent variable is negligible and Vuong's test does not justify the use of the ZINB.[6] In the light of this, we decided to use the NBRM, in which the variance is modelled as a quadratic term (NB-2). Equation (4) represents the general expression of the models estimated, taking into account the five groups of variables for the specific drivers of innovation described above:

[6] Test results are available upon request.

$$= + \beta_0 + \beta_1 \left(\text{Innov\_Sys}_{i,t-1}\right) + \beta_2 \left(\text{MarketSy}s_{i,t-1}\right) + \beta_3 \left(EE\text{\_Policy}_{i,t-1}\right) + \beta_4 \left(\text{Energy\_Sys}_{i,t-1}\right) + \beta_5 (EN) \left(\text{Controls}_{i,t}\right) + \varepsilon_{i,t} \quad (4)$$

We use a log-log fixed effects specification to take into account country-specific unobservable heterogeneity; Hausman's test confirms our choice of using fixed effects.[7] The maximum likelihood method is used to estimate the model parameters. All variables referring to the systems investigated are modelled with a one year lag in order to reduce potential endogeneity bias while preserving the standard inducement effect framework. In this sense, when the resilience of the innovation process is accounted for, it is commonplace to expect policies or market inducement effects to present a time lag from the time when the phenomenon occurs and the reaction in terms of innovations by firms. As a standard method of addressing this issue, a one year lag reduces endogeneity and enables resilience to be accounted for, but a minimal number of observations is lost.

Different model specifications are estimated to test the contributions of the different systems affecting the dynamics of invention of EE technologies. The policy variables are maintained in all the specifications, while different variables for measuring the contribution of other innovation drivers are tested. Moreover, further estimations show the impacts of each policy type by disaggregating the policy dataset according to Table 2.

Table 3 tests a general policy inducement effect together with the contribution of two different proxies of the innovation system. More specifically, estimations (1–4) include the stock of GERD, while in estimations (5–8) innovation capacity is measured by the specific stock of R&D in EE. Broadly speaking, the contribution to invention of the national innovation system is positive and significant both when the effect is tested on the total number of patents and when patents are divided into the three sub-domains. Unfortunately, our dataset suffers from a large number of missing data for specific R&D in EE, which translates into several missing observations. Therefore, in the estimations below we keep only the GERD variable for measuring the contribution of national innovation systems.

The price-inducement effect, represented by the price-tax bundle, also positively and significantly affects our dependent variable, although the statistical robustness is lower than for R&D. Since we measure prices at end-use level, it can be inferred that producers pay more attention to price changes, probably in a demand-driven effect in which consumers are highly sensitive to energy consumption and preferably choose high-efficiency goods to counterbalance increases in energy prices.

In the case of electrical appliances and lighting, two sectors characterised by intensive energy use but prompt responsiveness for energy saving, this effect is particularly strong, for at least two reasons: first, the lifecycle of lamps and appliances is shorter than that of buildings, and the reactivity of consumer's choices

[7] Test results are available upon request.

Table 3 General policy inducement effect on specific technological domains

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Patent count in EE-total	Patent count in EE-building	Patent count in EE-lighting	Patent count in EE-elec. appl.	Patent count in EE-total	Patent count in EE-building	Patent count in EE-lighting	Patent count in EE-elec. appl.
Stock of GERD	0.51***	0.52***	0.58***	0.66***				
	(8.87)	(8.74)	(6.41)	(5.84)				
Stock of R&D in EE					0.20***	0.20***	0.37***	0.32***
					(4.65)	(4.03)	(4.81)	(4.89)
Price-tax bundle	0.17**	0.13	0.45***	0.70***	0.13	0.04	0.50***	0.47***
	(2.19)	(1.49)	(4.44)	(4.90)	(1.33)	(0.36)	(4.20)	(3.38)
Stock of EE policy—total	0.22***				0.28***			
	(8.58)				(9.66)			
Stock of EE policy—building		0.19***				0.26***		
		(5.59)				(6.44)		
Stock of EE policy—lighting			0.47***				0.44***	
			(6.04)				(5.00)	
Stock of EE policy—elec. app.				0.71***				0.74***
				(10.41)				(9.62)
Constant	−5.64***	−5.94***	−7.00***	−7.94***	1.10***	0.82***	0.81*	0.11
	(−6.47)	(−6.67)	(−4.84)	(−5.18)	(4.20)	(2.96)	(1.81)	(0.26)
N	317.00	317.00	317.00	303.00	298.00	298.00	298.00	284.00
chi2	306.39	184.38	132.86	216.83	198.66	101.10	111.11	170.35

t statistics in parentheses; $* \, p < 0.1$, $** \, p < 0.05$, $*** \, p < 0.01$

in adopting more efficient goods reflects this quicker pace. Moreover, in the building sector the party that actually benefits from EE performance and pays the energy bill (the owner) is not the same as the part that constructs the building (the contractor). This is known in literature as the principal-agent problem: it describes a framework in which the 'agent' (the builder) may not always operate in favour of the 'the principal' (the building's owner or user). In this context, the builder might sub-invest in building dwellings with suboptimal EE performance, dumping the higher costs of energy bills on the future users (see also [41]).

With respect to the policy effect, in the general model specification a modest but positive impact of EE policies can be noted in regard to generating new patents, confirming the important role of public regulation in stimulating new economy-useful technologies [45, 69]. Moreover, the contribution of EE policies seems to follow the same trend as the innovation system, with the impact of policies being amplified in those sectors which are highly-dependent on R&D. For instance, the elasticity related to public regulation in the electrical appliances sector is almost three times the figure for buildings. The same trend can be found using specific EE-R&D expenditures in place of GERD.

The set of estimations shown in Table 4 provides a robustness check, enlarging the framework of analysis so as also to capture the effect of the energy (estimations 1–4) and environmental systems (estimations 5–8) as further innovation drivers. Although the main results remain largely unchanged, part of the variance in EE inventing activity can be seen also to be explained by the energy system and by environmental stringency. In more detail, when the energy system is tested, as represented here by a term showing the interaction between energy intensity and a dummy variable signalling the presence of nuclear power production, a significant, negative impact on new patents is noted, but only in sectors that use mostly electrical power (lighting and appliances). This means that those countries which make intensive use of energy are also less innovative in terms of EE, confirming our hypothesis that energy abundance reduces the stimulus to innovate in EE technologies. The same pattern, although lower, can be found when environmental stringency is examined, as measured by CO_2 emissions in the residential sector.

Finally, Table 5 tests the contribution of each single policy instrument to the total stock of EE patent applications. This last set of estimations provides some interesting insights for analysing the role of different policies. The first important remark that must be made concerns the size effect of different policy types, which is found to be rather similar in all cases. This result is particularly interesting, since economic theory has mainly relied on standard economic instruments (such as direct investments, taxes and subsidies) rather than on regulations aimed at improving the level of information and awareness of consumers.

Indeed, although the effect of economic instruments is positive and significant in terms of invention-related activity, a new point that emerges from our analysis is that other instruments also contribute just as much to the increase in EE patenting. Specifically, the impact of each policy instrument measured as elasticity is—on average—0.23 %, with the exception of voluntary approach instruments, which are found not to be significant. We believe that the most promising result is the

Table 4 The role of the energy and environmental systems

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Patent count in EE-total	Patent count in EE-building	Patent count in EE-lighting	Patent count in EE-elec. appl.	Patent count in EE-total	Patent count in EE-building	Patent count in EE-lighting	Patent count in EE-elec. appl.
Stock of GERD	0.50***	0.49***	0.73***	0.81***	0.53***	0.52***	0.84***	0.87***
	(7.67)	(7.20)	(6.14)	(6.77)	(7.39)	(6.81)	(6.32)	(6.96)
Price-tax bundle	0.17**	0.11	0.60***	0.81***	0.15*	0.09	0.54***	0.74***
	(2.06)	(1.28)	(4.60)	(5.12)	(1.73)	(1.01)	(3.97)	(4.54)
Energy intensity interacted with nuclear production	0.02	0.06	−0.32*	−0.66***	0.05	0.09	−0.23	−0.58**
	(0.21)	(0.77)	(−1.83)	(−2.81)	(0.53)	(1.01)	(−1.29)	(−2.50)
CO_2 emissions in residential sector					−0.05	−0.05	−0.20*	−0.12
					(−0.86)	(−0.82)	(−1.72)	(−1.24)
Stock of EE policy—total	0.22***				0.21***			
	(8.39)				(7.44)			
Stock of EE policy—building		0.20***				0.19***		
		(5.62)				(4.85)		
Stock of EE policy—lighting			0.39***				0.33***	
			(4.40)				(3.51)	
Stock of EE policy—elec. app.				0.59***				0.56***
				(7.64)				(6.82)
Constant	−5.55***	−5.59***	−8.79***	−9.86***	−5.86***	−5.93***	−9.86***	−10.53***
	(−5.76)	(−5.58)	(−5.14)	(−6.24)	(−5.75)	(−5.51)	(−5.40)	(−6.37)
N	317.00	317.00	317.00	303.00	317.00	317.00	317.00	303.00
chi2	306.52	185.50	134.95	222.17	302.52	182.12	134.31	219.20

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5 Inducement effect of alternative policy instruments on total patents

	(1)	(2)	(3)	(4)	(5)	(6)
Stock of GERD	0.56***	0.54***	0.59***	0.52***	0.63***	0.66***
	(8.79)	(8.05)	(9.27)	(8.07)	(9.97)	(9.84)
Price-tax bundle	0.20**	0.18**	0.18**	0.17**	0.15*	0.12
	(2.43)	(2.02)	(2.12)	(2.05)	(1.69)	(1.29)
Energy intensity interacted with nuclear production	−0.02	−0.02	−0.07	−0.04	−0.09	−0.12
	(−0.20)	(−0.23)	(−1.01)	(−0.51)	(−1.19)	(−1.62)
Stock of EE policy—economic instruments	0.26***					
	(6.93)					
Stock of EE policy—information and education		0.25***				
		(6.15)				
Stock of EE policy—policy support			0.21***			
			(4.59)			
Stock of EE policy—regulatory instruments				0.25***		
				(7.12)		
Stock of EE policy—RD&D					0.20***	
					(3.73)	
Stock of EE policy—voluntary approaches						0.15
						(1.50)
Constant	−6.39***	−6.13***	−6.90***	−5.89***	−7.57***	−8.07***
	(−6.76)	(−6.18)	(−7.30)	(−6.14)	(−8.10)	(−8.09)
N	317.00	317.00	317.00	317.00	317.00	317.00
chi2	261.32	237.14	220.22	268.11	196.40	161.15

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

contribution of information and education policies, which include energy labelling and performance codes for all three sectors considered.

Moreover, not only regulatory instruments such as codes, performance standards and other mandatory requirements but also monitoring activities, public research programmes and demonstration projects provide good stimuli for the growth of EE technologies and their impacts probably operate jointly in enriching the heterogeneity of the policy mix and hence the overall policy-inducement effect.

5 Conclusions

Our study provides a broad analysis of the drivers of innovation in EE by looking at the residential sector. As evidenced by the descriptive analyses on the trends in EE patterns and public policy interventions, cross-country specific features emerge which appear to be related to different levels of policy stringency adopted in the OECD countries during the last two decades in this field. The econometric analysis, based on an original dataset comprising sectoral patent data and information on specific policy instruments, confirms the importance of public policies as drivers of innovation activities in this poorly explored sector.

More specifically, this study highlights that national and sectoral innovation systems explain a large portion of a country's propensity to innovate in EE technologies within the residential sector. At the same time, environmental and energy systems are shown to shape the rate and direction of technical change in this sector, with energy availability playing an important role, as an abundance of cheap energy sources (such as nuclear power) tends to reduce the propensity to innovate.

Regarding the specific role of general and sectoral public policies, economic instruments such as energy taxation seem to have an inducement effect on the likelihood to innovate in energy saving devices. Moreover, public policies specifically designed to induce efficiency in energy consumption emerge as crucial for boosting the innovations in technology necessary to reach higher resource efficiency standards. In this respect, an analysis of the impact of different policies provides interesting, new insights. In particular, the econometric results point out that not only is the policy inducement effect on innovation relevant when standard instruments such as direct investments, taxes and subsidies are adopted, but its importance also extends to policies aimed at improving the level of consumer information and awareness. Among those policies, information and education policies, which include energy labelling and performance codes for the sectors considered, emerge as strongly capable of affecting innovation dynamics in residential EE technologies. Moreover, the closer the relationship is between agents paying energy bills and agents adopting efficient technologies, the higher the impulse is to innovate in the related technological domains, as clearly emerges from the analysis of the cases of lighting and electrical appliances.

These results appear to have significant policy implications and suggest a way to further develop research in this field. First, the jointly significant influences of innovation, energy and environment systems on innovation-related activities in the sector under examination confirms the importance of adopting a systemic perspective to the analysis of eco-innovation. Second, this implies that different policy dimensions working both on the multiple elements influencing innovation dynamics and at system level should be combined in a properly designed policy mix. Third, an appropriate policy mix should contain not only traditional market-based instruments as claimed by standard environmental economics theory in the past, but also information/education based instruments or policy instruments designed as voluntary approaches. Moreover, policy instruments should be planned so as to be as closely related as possible to the market of final use of technologies, giving the correct signals to those agents who invest in energy saving technologies. Finally, the emerging complexity of the policy mix in this field calls for specific attention to coordination problems so as to enhance the consistency and persistence of the whole policy strategy. On this issue, further efforts from both the scientific and policy communities are needed in order to increase understanding of policy interactions and consequently enhance the effectiveness of the policy framework adopted.

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Appendix

Table 6a Patent classes by technological domains and keywords

Main domain	Sub-domain	CPC class	Sub-classes	Keywords
Insulation	Heat saving	E06B	3/24, 3/64, 3/66, 3/67	
		E06B	3	High perform+ OR insulate + OR low energy
		C03C	17/00, 17/36	Low e
		E06B	3/67F	Vacuum
		E06B		Aerogel
		E06B	3/20	
		E06B	1/32, 3/26	Thermal break
		E04B	1/74, 1/76	
		E04B		Polyurethane OR PUR OR polystyrene OR EPS OR XPS OR heavy gas+ OR pentane OR insulate+

(continued)

Table 6a (continued)

Main domain	Sub-domain	CPC class	Sub-classes	Keywords
		E04B		Flax OR straw OR (sheep + AND wool)
		E04F	15/18	
		E04F		Sea shell
		E04D	11	Insulate+
		E04D	11	Green roof
		E04D	11, 9	Thatch+
		F16L	59/14	
	Water saving	F24H		Water AND (sav+ OR recover +)
		F16 K	1	Water AND (sav+ OR recover +)
		E03C	1	Water AND (sav+ OR recover +)
	Cooling reduction	E04F	10	
		C03		Glass AND (reflect+ OR sun-proof OR heat resist+)
		E06B	3	Glass AND (reflect+ OR sun-proof OR heat resist+)
		B32B	17	Glass AND (reflect+ OR sun-proof OR heat resist+)
High-efficiency boilers	HE-boilers	F23D	14	Low
		F24D	1	
		F24D	3, 17	
		F24H, excluding F24H7		
Heat and cold distribution and CHP	Heating system	F24D	5, 7, 9, 10, 11, 13, 15, 19	
	Storage heaters	F24H	7	
	Heat exchange	F28F	21	
	Cooling	F25B	1, 3, 5, 6, 7, 9, 11, 13, 15, 17	

(continued)

Table 6a (continued)

Main domain	Sub-domain	CPC class	Sub-classes	Keywords
	Combined heating and refrigeration systems	F25B29		
	Heat pumps	F25B30		
	CHP	X11-C04		
		R24H240/04 (ICO code)		
Ventilation	Ventilation	F24F	7+	
Solar energy and other RES	Solar energy	F24 J	2	
		H01L	31/042, 31/058	
		H02 N	6	
	Biomass	F24B		Wood+
	Geothermal	F24 J	3	
Building materials	Construction structures	E04B	1	Building+ or house+
	Materials	C09 K	5	Building+ or house+
Climate control systems	Control of temperature	G05D	23/02	
	Electric heating devices	H05B	1	
Lighting	Lighting	F21S		Not vehicle, not aircraft
		F21 K	2	Not vehicle, not aircraft
		H01 J	61	Not vehicle, not aircraft
		F21 V	7	House or home or building
	LED	H01L	33	Light and LED
		H05B	33	Light and LED

Source adapted from Noailly and Batrakova [57]

Table 6b Patent classes by technological domains and keywords

CPC general class related to each appliance		Technologies aimed at improving the efficiency of home appliances	Description
Refrigerators and freezers	F25D see http://www.cooperativepatentclassification.org/cpc/scheme/F/scheme-F25D.pdf	Y02B 40/32	Motor speed control of compressors or fans
		Y02B 40/32	Thermal insulation
Dish-washers	A47L 15/00 see http://www.cooperativepatentclassification.org/cpc/scheme/A/scheme-A47L.pdf	Y02B 40/42	Motor speed control of pumps
		Y02B 40/44	Heat recovery e.g. of washing water
Washing machines	D06F (excluding D06F31/00, D06F43/00, D06F47/00, D06F58/12, D06F67/04, D06F71/00, D06F89/00, D06F93/00, D06F95/00 as well as their subgroups). See http://www.cooperativepatentclassification.org/cpc/definition/D/definition-D06F.pdf	Y02B 40/52	Motor speed control of drum or pumps
		Y02B 40/54	Heat recovery, e.g. of washing water
		Y02B 40/56	Optimisation of water quantity
		Y02B 40/58	Solar heating

Source adapted from Costantini et al. [16]

Table 7 Countries

Country	Code	Country	Code
Austria	AT	Ireland	IE
Australia	AU	Italy	IT
Belgium	BE	Japan	JP
Canada	CA	Korea	KR
Switzerland	CH	Luxembourg	LU
Germany	DE	Netherlands	NL
Denmark	DK	Norway	NO
Spain	ES	New Zealand	NZ
Finland	FI	Portugal	PT
France	FR	Sweden	SE
United Kingdom	GB	United States	US
Greece	GR		

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Part III
Renewable Energy

The Cost of Renewable Power: A Survey of Recent Estimates

Ignacio Mauleón

Abstract This paper presents the results of an overview and survey of recent, up-to-date estimates of the cost of generating electric power from renewables. The results are based on actual data from projects already implemented or commissioned, and are organised as homogeneously and comparably as possible. Two main cost measures are considered: total capital costs, and its two main components, equipment, and remaining installation costs, and the Levelised Cost of Electricity (LCOE). An extended discussion on the definition and meaning of this latter cost measure is also provided in an appendix. The chapter closes with some reflections and forecasts of the likely scenario for the power business in the coming years.

Keywords Renewable power technologies · Levelized cost of electricity · Capital cost · Learning rates · Dispatchability

JEL codes Q00 · Q20

List of Acronyms

BNEF	Bloomberg New Energy Finance
BIPV	Building Integrated Photo Voltaic
BoS	Balance of system cost
CCS	Carbon Capture and Storage
CdTe	Cadmium-Telluride (PV cell)
CHP	Concentrated Heat and Power
CSP	Concentrated Solar Power
c-Si	Crystalline Silicon (PV cell)
DLC	Discounted Lifetime Cost
DLG	Discounted Lifetime Generation
DNI	Direct Normal Irradiance, (kWh/m^2/year)

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EIA	US Energy Information Administration
EPIA	European Photovoltaic Industry Association
EWEA	European Wind Energy Association
GCCT	Gas Combined Cycle Turbine
GHG	Greenhouse Gasses
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Association
kW	MW, kilowatt, Megawatt
kWh	MWh, kilowatt hour, Megawatt hour
LCE	Levelised Cost of Energy (same as LCOE)
LCOE	Levelised Cost of Energy
NREL	National Renewable Energy Laboratory
$O\&M_t$	Operating and Management costs in period t
PTC	Parabolic Trough Collector (also denoted simply as PT)
PV	Photo Voltaic
PwC	Price waterhouse Coopers
REN 21	Renewable Energy Policy Network for the Twentyfirst Century
SLCOE	Total System LCOE
TES	Thermal Electricity Storage
USD	US Dollar
vRES	Variable Renewable Energy Sources
WACC	Weighted Average Cost of Capital
WEC	World Energy Council

1 Introduction

[1]This paper is an overview of the cost of renewable power, based on the most recent, up-to-date research available at the time of writing late in 2013. It is important to underline this point from the start, because renewable energy is a rapidly evolving field, and in some cases costs have decreased substantially over the last year or two. Several research departments around the world are working on this subject, so an attempt to summarise and unify the main results as far as possible is not only worthwhile but absolutely necessary. This is so because the world of energy is undergoing significant changes that many consider will change the outlook of the industry forever within one or two decades at most [34]. The opportunities for investors and governments alike are therefore huge, but so are the potential losses for

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those who stick to the old way of producing and generating energy. The effects may be felt more quickly in some fields, notably electricity, and more slowly in transportation, but all will be affected sooner rather than later. The impacts will also be different depending on the stage of development of each economy, since renewable power requires a different type of network, which must be suitable for off-grid production and consumption. Thus, emerging and even less developed countries enjoy a comparative advantage precisely because their grids are not so well developed.

The paper focuses on costs for several reasons. First, they are a simple and effective way to compare different technologies from an economic standpoint, covering renewables and also fossil fuels. It is important that the measures chosen are clearly defined and can also be estimated precisely and homogeneously, i.e. comparably. This is why all research focuses on the Levelised Cost of Energy (LCOE), a widely accepted measure in the industry, which enables useful comparisons to be made across technologies, geographical sites and different research studies. It is important to remark from the start that no externalities of any kind are considered, and in particular no subsidies or any other form of public support. For the sake of comparison, an equivalent measure for fossil-fuel generated power is presented in which subsidies are not considered either [15]. Second, several renewable technologies are still not competitive at market prices, and that is why an analysis based on measures of return rates is not yet possible, though this is quickly changing, as is discussed below.

Renewable power generation costs are declining quickly in some cases, so it is difficult to keep well informed and up to date. This lack of information and the sometimes negative perceptions about costs and characteristics have a negative impact on their deployment. For investors this implies a greater risk, and thus requires higher rates of return. But with precisely up-front capital cost being the main cost component in the case of renewables this has a major impact on the final cost of many projects—these points are discussed at some length in the following sections. Governments lack the information that they need to design effective or less costly support policies, and provide consumers, and indeed society as a whole (which may be susceptible to unfounded negative perceptions and prejudice) with objective information.

The paper focuses only on electric power, omitting heating power and transportation. Also, only technologies for which sufficient data are available are considered. This is why solar thermal technology, all forms of sea power technology and most bio-energy sources, among others, are not considered. This should in no way be taken as meaning that they are not significant, or at least will not become so in the near or distant future in the cases of those that are currently at the research or demonstration stages.

As noted in one of the research reports analysed "Any quantitative report or study is only as good as the data and other information used for its production" [41]. Accordingly, the results presented here come from a variety of studies, but are mainly based on the Irena costs series, which in turn are derived from their extensive data base of around 8,000 medium to large-scale commissioned and proposed renewable power generation projects, from a wide range of data sources all over the world [18–23]. Other sources which are more comprehensive but based on estimations, or are more specific, have also been considered [8, 29, 41]. As a final point, most results presented are valid at a given moment in time, and with this field developing so rapidly some forecasts or projections are inevitable if the analysis is not soon to become outdated. The discussion in the final section, based on observed past trends, comments and opinions of market participants as reported in recent enquiries, is intended to fill that gap.

The next section presents the cost measures used in the paper and analyses them in some detail. The LCOE in particular is considered in greater depth in an Appendix as well. Section 3 is the main section of the paper: it reports the results for the six technologies considered: Concentrated Solar Power, Solar Photo Voltaic, Wind power, Hydropower, Biomass power and Geothermal. Some assessments of future deployments and cost reductions are discussed for each one. Section 4 briefly outlines the main results and addresses the assessment of future trends in the market and different technologies. Although it is necessarily somewhat tentative, an attempt has been made to base it on a detailed analysis of each technology and the interrelations that will derive from them. In particular, it is observed that the very concept of individual costs will be superseded by joint evaluation. An appendix that addresses the LCOE measure in some detail, a list of acronyms used in the report and a list of bibliographical references close the chapter.

2 Measures of Costs

Cost measures are obviously relevant in the financial analysis of any proposed investment, and more so when investments are not competitive at market prices, as is the case of most renewable energies today (though this is quickly changing). Consequently, the proposed investment will usually require some kind of public support in one way or another. When technologies are competitive in market conditions other measures may be considered, such as the net rate or return, etc. At the precompetitive stage, however, cost measures are highly relevant in order to assess the distance to ‘grid-parity’ or competitiveness in broad terms, and to make comparisons between several technologies. This is the purpose of the main cost measures considered in practice by almost all market players. There are several possible cost measures, each with its own merits and pitfalls but all with their insights for specific purposes. And while there is no single clear, general measure of cost, it suffices for them to be properly understood and used for the specific end for which they were designed.

At this point a digression is in order concerning measures of cost, depending on the type of literature source considered. In much of the academic work published, researchers tackle this issue by taking into account two fundamental, related questions: the value of the CO_2 avoided -especially for renewable technologies-, and the costs of grid integration. The former is generally considered to be relevant but very hard to assess in monetary terms; it is also frequently concluded that there are less costly ways of avoiding those CO_2 costs than resorting to renewables ([26] is a representative example). Most researchers focus mainly on the latter question, i.e. the costs of grid integration. This is because by their very nature renewable energies are intermittent and unpredictable: they depend on the vagaries of the wind and sun, although the unpredictability applies mainly to the wind, as the sun is variable but more predictable, at least a few days in advance, and throughout the hours of the day. Since demand must be adjusted at all times, because electricity is currently hard or indeed impossible to store in large amounts, the immediate conclusion is that variable Renewable Electricity Sources (vRES) need some kind of 'back-up' generating capacity. Hydraulic energy is one possibility, but in practice the task is usually assigned to natural Gas Combined Cycle Turbines (GCCT), which are a fossil-fuel-based source. This may represent a substantial cost, as this capacity must be kept waiting in *stand-by position*, i.e. operating but at low levels, and for technical reasons such plants cannot be quickly started from zero on short notice, at least at a reasonable cost.

Interestingly, from the point of view of market participants the question has been analysed much more openly, in a manner based on the actual functioning of electricity markets. And the fact is that experience seems to contradict academic concerns to a large extent to judge from the high rates of penetration of renewables achieved in some markets (Germany, Denmark, Spain and elsewhere) and the results of some enquiries. One interesting example is a survey conducted among system operators by the European Photovoltaic Association (EPIA): the main result obtained is that even as it stands today the electricity network can accommodate quite large amounts of renewable energy without significant disruptions [10]. This is all the more remarkable given that the actual grid is not designed for renewables. That would require a 'denser' net at local levels -because of self-consumption and distributed generation- and a few long distance connections capable of carrying large volumes of electricity [32]. It must also be noted in passing that the cost of investing in the network and the losses incurred in the transportation of electricity are greatly reduced with renewables and distributed generation and consumption at local level.

Finally, this is just one of the many externalities involved in the analysis of the cost of renewable energies. It is significant, but so are many other externalities in the present context. A brief discussion of this point follows later in this section. Therefore, without denying their relevance, the fact that all externalities in general are difficult or almost impossible to measure properly in monetary values results in their not being considered in the present case. This is in no way to imply that they should not be taken into account, but rather that as a first step it is best to have a simple cost measure such as the LCOE or some other that can be easily assigned a monetary value and can be used to make meaningful comparisons.

The point of view usually followed at present is that of an investor, be it a private company, an individual, or the state. Therefore, it is not strictly cost that is being considered but rather the price that has to be paid in the market to go ahead with the investment in question. This is important, since the profit of suppliers of equipment and other services is thus included in the price paid by the investor; that profit may vary substantially from one location to another depending on the competitive conditions of specific markets. This may also be more relevant with equipment that is not so easily tradable, such as wind turbines, and less so for Photovoltaic (PV) panels, which can easily be transported at low cost.

It should also be remarked that there is another point of view that is becoming more and more significant in this field: that of the consumer. This is because the price paid by consumers for electricity can be as much as three or four times the market price at which the investor sells the electricity generated. The impressive recent cost reduction in PV technology has made it competitive for consumers to produce and consume their own electricity in many parts of the world -that is, 'grid parity' is being achieved at consumer level-. Interestingly the concept of LCOE is more relevant if the market price of electricity is constant, which is usually the case for consumers, at least to some extent, but not so much for generators-investors, who must generally deal with highly variable prices, even within a single day. This point is discussed at some length in the appendix.

Three main measures are considered here and presented in the next section: (1) the cost of equipment at factory gates; (2) the total installed costs, which usually involve substantial amounts of cash to prepare the specific site where the equipment is to be located, financial fees charged by banks, etc.; and (3) the Levelised Cost of Electricity (LCOE), the most common measure considered by market players to assess and compare the cost of different technologies (briefly defined below, and discussed at greater length in the appendix). The first two are given in monetary units per unit of capacity, for example USD/kW, and are straightforward concepts that need no further explanation. The third, and perhaps most relevant, gives the monetary value of the energy generated per unit of time, e.g. USD/kWh. This last concept requires a more precise definition, which is duly given below. It should be remarked that no externalities or public support measures of any kind are considered. The definition is quite general, which means somewhat simplistic, and in the appraisal of specific real projects much more detail should be taken into account. But in order to make comparisons across technologies and geographical sites, specifying more detail may give the misleading impression of a better measurement when in fact all the information required may not be available in some cases, leading to somewhat biased results.

The LCOE is defined as the discounted value of all future lifetime costs, divided by the discounted amount of all electricity generated in the lifetime of the project. It is intended to provide a value for the total lifecycle costs of producing 1 MWh or any other equivalent measure of generated power with a given technology. It is defined in symbols as follows,

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{t=n} \left(\frac{I_t + \mathrm{O\&M}_t + F_t}{(1+d)^t} \right)}{\sum_{t=1}^{t=n} \left(\frac{E_t}{(1+d)^t} \right)}$$

where,

I_t, represents the capital cost expenditures in year t
$O\&M_t$, are the operating and management costs in year t
F_t, is the cost of fuel in year t
E_t, is the amount of energy generated in year t
d, is the discount rate
n, is the expected lifetime of the investment

The capital costs include the possible repayment of debt and interest, and equity if any, including a return required by investors. A Weighted Average Cost of Capital (WACC) is assumed in the calculations, which is usually 10 %. It therefore includes the standard profit for the investment considered in the market, including a risk premium. The cost of fuel in the case of renewables is zero except for biomass, but the definition can be applied similarly to non renewables for the sake of comparison. Operating and management costs are generally a small proportion of the total cost of renewables, with the up-front costs being the major component. This is in sharp contrast with non renewables, where the proportion of fuel costs is generally far greater, given also their likely variability (except in the case of nuclear energy). The energy generated depends crucially not just on the lifecycle but on the capacity factor, i.e. the number of hours that the equipment is effectively producing energy (close to 90 % in the nuclear case and between 20 and 35 % for solar, depending on locations). The expected lifetime of energy investments ranges generally between 30 and 50 years, with the exception of hydraulic and nuclear, for which it can reach 80–90 years. This may greatly affect the LCOE depending on what discount rate is chosen.

The measure may be questioned on several grounds, but has the virtue of being relatively simple to calculate and understand, thus allowing communication between different players. It is usually admitted in practice in the market by supporters of vRES and detractors alike. All these points deserve at least some discussion and clarification, but this is deferred to the appendix.

Before leaving this subject it may be worth commenting on a new measure that focuses precisely on grid integration: the Total Net System Cost. Somewhat surprisingly for a vRES technology, it focuses on the Concentrated Solar Power (CSP) with Thermal Energy Storage (TES) [6]. The basic argument put forward by proponents of this solar technology relies on its storage capacities, whereby it can sell electricity taking advantage of the ability to transfer power from times of low demand and prices to high price and demand times, i.e. it is dispatchable within a range of a few hours or even days. It can also very easily be ramped up and down much more cheaply than the procedure currently used for that purpose, which relies on GCCT. Proponents also argue that besides generating more profits than are recognised in a simple measure such as the LCOE, the technology can provide stability to the grid in the form of spinning and ancillary services, providing back-up capacity at low cost and other services such as maintaining voltage, frequency, etc. The LCOE for this technology is quite high, and there are no clear perspectives for reducing its costs quickly in the near future. But while all these advantages are certain and sizeable, they are difficult to measure and are not considered further here (though this does not mean that we deny them in any way).

There are several kinds of positive and negative externalities that are usually mentioned when discussing the topic of renewable energy. The first positive externality for renewables is undoubtedly related to the climate and the emission of CO_2 and other polluting gasses. This is clearly relevant, and has become more so since the last report of the Intergovernmental Panel on Climate Change ([17] with an updating announced for 2014), and hardly anyone denies it. But the weight given to it ranges from fairly low to considering it as one of the most relevant problems facing human kind.

The second, highly relevant positive externality relates to macroeconomic performance: renewables can bring green jobs, reduce the current account deficit (or improve it if it is already positive) and thus improve the security of the energy supply. These advantages are, however, mainly applicable to countries where fossil fuel and gas reserves are scarce and there is an unemployment problem, such as the European Union at present (Spain is an outstanding case in point). But even for countries with plenty of fossil fuel resources of one kind or another, renewables can provide a useful way to diversify the economy and help avoid the threat of the so called 'Dutch disease' [4]. This is precisely why many oil and gas-rich countries are investing heavily in renewables and exporting their fossil resources (Saudi Arabia, the United Arab Emirates, Brazil, Norway, Denmark, etc.). Finally, renewables are suitable for distributed generation and consumption of power, and they can greatly reduce the cost of heavy investments in networks and the losses incurred in transporting energy from major supply facilities to large consumption sites (cities, large factories, etc.).

The third and most easily identifiable positive externality entailed by renewables is a consequence of the fact that since variable costs are low in relation to fixed up-front capital costs it is always more profitable to operate plants and generate electricity than to disconnect them. This will necessarily bring down the electricity market price, and that may have a very sizeable impact, especially on standard marginalistic markets (i.e. it is the highest price that is brought down). This was discussed quite early in the relevant literature in relation to wind energy deployment in Denmark and Germany: it is called the 'merit-order effect' [11]. This is the justification behind paying 'feed-in tariffs' for renewables. In the end, even if the cost of 'feed-in tariffs' is added to the electricity price, the general result is that renewables are beneficial for consumers.

A fourth, frequently neglected positive externality derives precisely from the relatively low variable costs of renewables, since with the exception of biomass no fuel costs are incurred, in sharp contrast to fossil-fuel energies. One immediate implication is that with the uncertainty surrounding the future supply of fossil fuels, project costs are becoming much harder to assess, implying a considerable risk that must be included in the capital cost required from investors.This extra cost is avoided with renewable energies.

The main negative externality, as pointed out and discussed at length in Joskow [13, 14, 26] and Ueckerdt [39], is the cost associated with grid integration, because vRES, by their very nature, require back-up energy. Since this must be weighted against what they see as the only positive externality—the cost of CO_2 emissions avoided—they conclude that there are cheaper ways to achieve that end, such as Carbon Capture and Storage (CCS) technology, based on capturing CO_2 at the point of burning fossil fuels and drilling to store it deep underground in mines and exhausted oil and gas deposits. These technologies are well known to oil and gas extracting companies. In this context, it should also be remarked that coal and oil-fired power plants also need back-up energy, given that they cannot be ramped up and down quickly and at reasonable cost. Gas plants are the usual fossil-fuel option for balancing the power system, but again they cannot be ramped up and down on short notice at reasonable cost, so they have to be kept on stand-by, which implies a considerable cost. Again, other authors argue that these alleged integration costs are difficult to measure, and are relevant for a traditional grid not designed for renewables, which require a quite different type of electricity network [32]. Grid integration and balancing capabilities have also been discussed at some length above, and it has been remarked that, a positive rather than a negative externality should be accounted for precisely for CSP with TES.

In relation to grids and electricity networks, it must be added that the discussion above applies to countries with reasonably well developed electricity networks. This is not the case for much of the world, however, and it is precisely here that one of the main comparative advantages of emerging and less developed economies lies. Grids can be designed from scratch or redesigned much more easily according to the requirements of renewable energies. And totally off-grid systems or small local grids will very likely take the place of traditional 'developed' electricity networks. The huge costs involved in setting up and deploying a traditional electricity grid, and the losses incurred in transferring electricity over long distances are thus largely avoided in the new mode of distributed generation and consumption of electricity. In the end, summing up the discussion, when the question of 'grid-integration' of vRES is properly assessed, it cannot be sustained that it is a sound, clear negative externality: it may even be an advantage in certain circumstances. Finally, to be fair, other more academically oriented papers are far less critical of vRES ([5, 12, 33] are recent examples).

Last but not least, subsidies for fossil-fuel energies must be mentioned at least in passing [15]. Such energies in fact receive several times the amount allocated to renewable energies. It is true that they also generate a far larger amount of energy, but what is astonishing is that even after more than two centuries for coal, one and a half centuries for oil and gas and several decades for nuclear power they still need subsidies and public support to be worth operating. In sharp contrast, renewables have been subsidised sizeably, in one way or another, for just the last two decades and are nevertheless the target of severe criticism by many.

Finally, externalities may represent huge costs or benefits, and all possible effort should be made to assess them. But they are difficult to evaluate and subject to a considerable degree of uncertainty and opinion, and hence it is difficult to assign precise monetary values to them. It is always worth starting with a clear, simple measure such as the LCOE, provided that it is well understood, i.e. does not include public support or externalities of any kind. If the policy maker wishes to include externalities in the assessment, then all of them, positive and negative, should be included.

3 Cost Per Technology

This section addresses the main focus of the chapter, i.e. costs per technology. The technologies considered are CSP, solar PV, wind power, hydro power, biomass power and geothermal, in that order. These technologies are selected because there is sufficient and reliable observed data on which to base some conclusions.

Their availability and cost at world level varies markedly, but they exist to some extent everywhere, which justifies the universality of the approach. However, the high level of availability of wind and solar sources has garnered public support, resulting in a large-scale, increasing deployment which in turn has decreased costs significantly because of the well known 'learning-by-doing' effect. These decreases in costs, in turn, have helped increase deployments, so that a kind of 'virtuous circle' has activated the implementation of these technologies even further. This effect is not so marked for other technologies, though they may contribute in crucial ways to joint deployment of renewables.

A brief technical description of each technology follows, together with a summary of its recent history, if any and an overview of its current situation and future prospects based on the analysis above (not necessarily in that order). Specific costs are presented and discussed at the end of the section in two condensed tables. Two cost measures are discussed: the LCOE and total capital costs. Some observations on Operation and Management costs (O&M) and fuel costs are also presented and discussed where appropriate.

3.1 Solar CSP

CSP technology is based on the Direct Normal Irradiance (DNI) of the sun on the surface of a heliostat (curved mirror), which concentrates sunlight either on linear Parabolic Trough Collectors (PTC) or onto a point in a solar tower. The light is then focused on a liquid that reaches a high temperature (400–600 °C) and is then either conducted to generate steam and power directly or stored in the form of heat in another liquid suitable for that purpose (molten salts, usually), which is employed to generate steam and power at a later convenient time (TES). Other less common technologies are also available, such as the linear Fresnel collector and Stirling dishes (see [17, 20]). Some common, relevant aspects in all cases are that they require large, fairly flat spaces to install the mirrors, and that considerable amounts of water are required to clean them. This is because the system must be large for technical reasons.

The complexity of the system lies in the need to focus the heliostats very precisely on the sun's rays throughout the day, and also concentrate that light very precisely onto the required receiving point. The preparation of the site (including the placement of the heliostats) and the technical mechanisms to ensure the correct focusing of the system make the up-front installation costs quite considerable: a 100 MW system with 6 h. of storage in an OECD country may require an up-front investment of USD 800 million (see Table 2). Given that CSP systems are targeting 1 GW size, the initial disbursement becomes quite high.

Some economically relevant points stand out already from this short description: the technology is not downward scalable, and it requires a large up-front investment; it also requires direct solar irradiance, and does not therefore capture indirect or diffuse irradiance; large, fairly flat spaces are also needed; it allows storage, directly in the form of heat, so there are no significant energy losses in the process. These three aspects also stand out clearly as significant differences from the other main solar technology, i.e. PV.

Since it can be stored for a few hours, the technology is dispatchable at will in a time frame ranging from a few hours to one or two days, which means that the generation of power can be decoupled from its consumption and transferred from times of high irradiance to times with high demand, or peak demand times (when the electricity price is usually also higher but the irradiance is lower). This is a crucial property of CSP systems with TES that makes it more profitable than other intermittent renewable, technologies in this respect. By contrast, it is only suited to places with strong, constant solar irradiance, typically more or less close to the equator, whereas PV works almost anywhere, even under cloudy weather. Since a CSP system must be large, it is suitable for the current type of generation and consumption model, which implies that it also requires the current type of electricity network, designed to transport electricity from large generating plants to large consumption centres, typically big towns and factories. It is not suitable, therefore, for the distributed-generation model based on modular technologies used with almost all other renewable technologies.

From the point of view of cost comparisons, it must be remarked that the LCOE measure is less relevant in this case, since it is more appropriate for a constant selling price of electricity (see the appendix). In fact, some researchers are proposing another measure, purported to be more adequate: the total System LCOE cost (SLCOE; see [6]). This measure takes account of the ability to capture the income from peak demand and prices but also to offer 'stand-by' and back-up energy to the electricity network. Since the energy is stored in the form of heat, it can be transformed to steam and power in a matter of a few seconds, or even less, so that it can also provide ancillary services to the network (stabilising voltage and frequency, and other properties). All of these add considerable value to this technology as compared to others.

Capital costs for this technology may range from a low of USD 3,500/kW for a PTC system with no storage in a developing country to a high of USD 10,500/kW,

Table 1 Levelised cost of electricity (2012) renewable technologies

Wind
Onshore: 0.06–0.14
Best sites US: 0.04–0.05
Offshore: 0.15–0.19
Small scale: 0.16–0.40
PV
Utility scale: 0.13–0.31
Good sites: 0.11
Residential/off-grid: 0.20–0.45
CSP
Parabolic trough: 0.20–0.36
Solar tower: 0.17–0.29
good sites: 0.14–0.18
Biomass
Typical: 0.06–0.15
Good sites: 0.02–0.06
Geothermal
Typical: 0.09–0.14
Good sites: 0.05
Hydro
Small: 0.02–0.13 (0.27)
Large: 0.02–0.19
Upgrading/refurbishing: 0.01–0.05
Fossil (OECD): 0.06–0.13
Diesel-fired: 0.35–0.50

LCOE quoted in USD/kWh
Values in parenthesis are for some extreme obs

i.e. three times as much, for a solar tower system with 6–15 h of storage in a typical OECD country. Generally solar tower systems are more expensive than PTC, but they are also more efficient since they achieve higher temperatures: storage also adds considerably to costs, and in developing countries costs tend to be lower because of lower labour and other local costs (see Table 2). For the LCOE, with all the caveats noted previously, for an average PTC system they stand in the range of 0.20–0.36 kWh. The LCOE for solar towers is somewhat lower, in the range of 0.17–0.29, due to efficiency gains derived from the higher temperatures achieved, and on good sites it may be as low as 0.14 kWh (see Table 1). Taken at face value these figures imply that the technology has a long way to go before it reaches competitiveness or grid parity. But they must be carefully weighted, given the other factors discussed before, so that perhaps a system cost analysis may be more adequate in this case.

Table 2 Total capital costs (2012) renewable technologies

Wind	
Onshore OECD	1,800–2,200
Onshore China/India	925–1,470
Offshore	4,000–4,500
PV	
Ground-mounted utility-scale	1,720–2,160
(c-Si; China, India, Germany)	
Residential roof-top	3,100–3,400
(China, California, Italy)	
CSP	
Parabolic-trough.	
No-storage	
OECD	4,600–8,200
Developing	3,500–4,000
6 h. storage OECD	7,100–9,800
Solar tower 6–15 h. storage	6,300–10,500
Biomass	
Co-firing	140–850
Stoker-boilers	
Developing	660–1,860
OECD	1,880–4,260
Gasification	2,140–5,700
CHP	3,700–6,800
Geothermal	
Condensing flash	2,000–4,000
Binary cycle	2,440–5,900
Hydro	
Large	1,050–4,200 (7,600?)
(additions)	500–1,000
Small	1,300–5,000 (8,000?)
Develp.	500 (min.)

Costs quoted as USD/kW
Costs include equipment and installation costs
Values in parenthesis are for some extreme obs

Although the technology itself dates back to the beginnings of the twentieth century in Egypt, it has only been deployed at market sizes fairly recently, and has focused mainly on the PTC system. The solar tower system and storage capabilities have only recently been added, although most new installations are of this type, i.e. solar tower with storage. This is because of their higher efficiency levels achieved and dispatchability. As for cost prospects, it is difficult to make precise forecasts based on estimated past learning rates, since there are no sufficiently long historical data sets. A modest value of 10 %, may be safely assumed though. The development of the market is not so strong as for PV, given that it is suitable for a more restricted environment and type of production/consumption system. Nevertheless, there are many projects being deployed around the world, mainly on good sites in emerging and other more or less developed economies (South Africa and the USA, for example). The list includes several Middle East countries (notably Saudi Arabia and the Gulf Emirates) and countries in the North of Africa (Morocco and Algeria). Therefore, the 'learning-by-doing' law can be expected to continue to apply, and consequently costs will continue to come down.

As for efficiency improvements, although research is ongoing there have been no significant results announced that would imply a big break-through. But as in any other field, if deployment continues future improvements can be expected. Adding all this up, capital costs are expected to decline by 2020 by as much as 28 % for solar tower systems, and in the range of 17–40 % for PTC (see Table 3). Interestingly enough, increasing the storage capacity simultaneously with the solar field does not increase the LCOE, which means that large solar plants can generate higher profits because of the dispatchable capabilities of CSP with storage [20]. It must be noted also that the LCOE is very sensitive to the irradiance level: according to some calculations irradiance increases and LCOE decreases may go hand in hand, i.e. a 10 % DNI increase may reduce the LCOE by 10 % [27]. Adding all this up, a future of plants concentrated in places of maximum irradiance can be expected (2,500–2,900 DNI), and of the solar tower type with storage up to 18 h. or even more, with quite large solar fields, so that heat not used for immediate power generation can be conveniently stored.

Recently, though, linear Fresnel technology with storage has been advocated. However, even though the capital costs are lower than for solar tower or PTC systems, its efficiency is also lower so it cannot be considered as a clearly superior option, though this may change in the future, of course. Some projections for the year 2020 are presented in Table 3, and although they do not augur 'grid-parity' it must be remembered that the LCOE cost measure may not be the most adequate in this case. The LCOE for solar tower systems may come down to the range of USD 0.12–0.16/kWh, and for PTC with storage to the range of USD 0.11–0.14/kWh.

Finally, it may be worth remembering that, as pointed out above, once renewables achieve a substantial share of the market they must be looked at from a joint perspective so that potential synergies can be unlocked. This is especially so in the case of solar energy, since PV and CSP technologies complement each other in many respects.

3.2 Solar PV

Until recently solar PV energy was little more than a curiosity. However, the recent rapid decline in costs, by whatever yardstick they are measured, has taken politicians, major utilities and the market in general by surprise, though not the traditional supporters of the technology. The importance of this particular technology cannot be overstated in the field of energy, and only a brief summary of the main points is offered here. Data on costs are mainly available for module and PV cells (W, or kW.), and not so much for LCOE (kWh.). This is a limitation, but one that is unavoidable given the fairly recent mass deployment of PV systems. Perhaps their most relevant feature is the steady decrease in costs from 1979 to 2012, with an average learning rate of 22 %: a total decrease from USD 14–0.9/W for Crystalline Silicon (c-Si) and Cadmium Telluride (CdTe) thin-film modules -the most common technologies-, and an accumulated decrease of 70–80 % in 2011–2012. These impressive data are the result of continued support on a world scale, although it has been intermittent at country level. The big push in the 1980s was made by Germany, and continues today. Other countries have come along in the process, although not so regularly: they have been mainly Europeans, but lately China and the USA have taken major steps forward too. The main channel of support—the 'feed-in tariff'—was defined and first implemented in Germany, and later implemented in most other countries too. It is essentially a price guarantee for the energy generated.

The reduction in costs has been brought about by the well known process of continued 'learning-by-doing', as a by-product of continued, mass deployment [28]. The last step in this process was the development of techniques and processes of assembly-lines in Germany. These were later sold to the Chinese, who deployed them on a large scale, operating as usual with far lower salaries than in Europe. The final result is well known from other industries: the German and other European factories have gone out of business, and almost all the world's PV module factories are now located in China. The earlier trends have slowed somewhat in 2013 as a result of the Euro crisis, which has resulted in a forced reduction of public support for renewables across the EU.

The cost of PV systems is highly variable due to differences in solar irradiance, different types of technologies (roof or ground mounted, with one or two sun tracking axes or indeed with none), and other characteristics of its specific market such as labour costs, competition, public support measures in place, etc. This further hampers efforts to draw up precise cost measures, particularly as compared to other more mature technologies such as hydraulic and biomass. Some figures can be given though: at the end of 2012, total PV installation costs, or system costs, were in the range of USD 1,700–2,200/kW for ground-mounted utility-scale systems in the most competitive places (China, India, Germany) and USD 3,100–3,400/kW for competitive roof-top systems (in China, California, Italy). The LCOE was in the range of 0.13–0.31 kWh. for utility scale projects, and as low as 0.11 kWh. at good sites, whereas for residential and off-grid systems—mainly roof-top—the LCOE was in the range of USD 0.20–0.45/kWh. These figures are getting close to grid-parity, or competitiveness without the need for public support, and in several places that level has already been reached for utilities and residential systems. Note that electricity prices excluding taxes are 3 or 4 times higher to consumers than at the producer level in many markets around the world. As for off-grid systems, PV systems with batteries are a less costly option than diesel generation—the usual alternative—almost everywhere. This also includes island systems.

The figures above are for c-Si modules. For thin-film technologies, mainly based on CdTe cells and modules, the cost per W is generally slightly lower, but this does not translate into lower LCOEs because of the significant difference in efficiency: for the CdTe cell the figure is in the range 6–10 % whereas for c-Si it is more than double that, at 15–20 %. In spite of this, and although at a much lower scale, thin-film modules are being deployed at commercial level, since they can be easily integrated into buildings, particularly where there is glass that also allows light through (Building Integrated PV (BIPV)).

The most difficult part of this discussion, but also the most challenging and relevant, concerns the future prospects for continued cost reductions and mass deployment of PV systems of all types. Some things are clear: the versatility of this technology (scalability from domestic to utility scale systems, adaptability to different types of consumer -residential, industrial, commercial- and off-grid systems including islands), makes its future look rather promising at world level [3]. This is especially so for countries and territories where modern electricity networks are not properly developed, i.e. for most of the world, including virtually all emerging markets, the whole of Africa and less developed countries elsewhere. For developed countries, mainly OECD, the technology is especially suitable for distributed generation and consumption, i.e. residential use, small to medium industry and commercial firms, as a consequence of its scalability and democratic character.

In spite of all this, the future hinges crucially on the future evolution of module and system prices and the LCOE, which also depends in turn on possible efficiency improvements. For one thing, it is clear that PV-module prices cannot go on decreasing at past rates for long, since they have already reached fairly low levels. Moreover, their share in total system costs has decreased considerably and is no longer the main component. Costs will therefore have to be brought down via Balance of System (BoS) cost components such as inverters, miscellaneous electric equipment, mounting racks, administrative costs of various kinds, labour and site preparation. There is still ample room for this downwards trend to go on, associated with the continued mass deployment of the past two or 3 years. But while it is true that the European market has stalled to some extent, the Latin American, Middle East, and other emerging markets have taken the lead and are investing heavily in all kinds of renewables, including PV. Thus, the 'learning-by-doing' cost reduction effect can be expected to continue working.

The main cost measure, i.e. the LCOE, can also be cut down by improving efficiency. The current commercially available efficiency levels are in the range of 15–20 % for c-Si cells, and 8–10 % for CdTe. However efficiency levels of up to 40 % for c-Si cells and up to 30 % for CdTe at pre-commercial stages have been reported by researchers in R&D laboratories. It is also of interest to note that the maximum attainable efficiency for concentrated solar PV cells has been reported to be around 90 %, although this technology is still at its early laboratory development [22]. Nevertheless, mass deployment and cost reductions will bring with them increased profits and funding for research, so that future efficiency improvements can be rightly expected. Reductions in public support schemes can also be expected to encourage cost reductions, because part of the support received by the demand side is appropriated by producers of PV modules and system installers and added to their profits as a result of the market interplay between supply and demand. Lastly, in spite of the high tradeability of PV modules, which ensures internationally homogeneous prices, the variability in PV system prices and costs is likely to continue, since there are many other factors that influence PV system installation costs and the LCOE.

Summarising, because of their many advantageous properties and the continued support that they enjoy in many parts of the world, substantial price and cost reductions can be expected in the near future for all kinds of PV system, and significant up-grades in their efficiency within two to 5 years. Thus, PV systems of all types will soon be achieving grid-parity in many parts of the world. It should be noted in this respect that reality has systematically outperformed cost reduction forecasts in the recent past (see e.g. [31]). This can be confirmed by comparing the data presented in Tables 1 and 2, offered in 2011–2012 by several research think-tanks, to casual observations of the market at the time of writing this chapter, i.e. the end of 2013.

3.3 Wind Power

The most common wind power technology is onshore turbine towers, set up in farms with good wind resources, i.e. high speed, the maximum feasible consistency and high capacity factors. The power generated is directly proportional to the cube of the wind speed and the square of the blade diameter. Wind speeds are faster at higher altitudes, which explains why turbine heights have increased over time. Moreover, at lower heights turbulence caused by terrain irregularities is more marked, making the generation of power less efficient. Turbines generally work at between 15 and 45 kph: faster wind speeds can damage them, so they have to be stopped if such speeds occur. The rotating shaft can be perpendicular or parallel to the tower, though the latter case is less frequent and is better suited for smaller, lower-power turbines (mini-wind power technology). Lately, more attention is being paid to offshore technology, i.e. wind farms deployed at sea, on relatively shallow shelves. This is because the wind at sea is usually more regular and frequent, and blows at higher speeds. But the scope of this development is more limited, since it requires shallow shelves far enough from shore and not too harsh sea weather. The sites in northern Europe—Scotland, Denmark, north of Germany, etc.— are among the best in the world.

The basic technology has been known since the beginnings of the electrical era, and started to be deployed significantly in the 1970s and 1980s at experimental levels. Since then, it has experienced substantial growth, mainly in European countries, with Denmark pioneering it and Germany and Spain following closely. Today it is still growing, but at a slower pace, partly because of the general decrease in support for renewables in Europe and, remarkably, due to the competing growth of solar technologies, mainly PV. Nevertheless, continued support is coming from emerging markets and the fact is that it is second only to hydro power in the ranking of shares attributable to renewable technologies with a higher share at the world level.

The consistent trend towards higher, taller turbines which has continued uninterrupted since the initial deployments is also striking. This can be partly explained by the higher wind speeds at higher altitudes, and by the fact that blade diameter can thus also increase. Substantial efficiency improvements can be very achieved, but turbine costs increase hand in hand with them, so that in the end the LCOE does not improve significantly. Thus, one possible explanation for the trend is that increased up-front costs raise a financial barrier that prevent the entry of smaller competitors.

The power generator mechanism is well known, but requires careful monitoring and frequent adjustments, so O&M costs are considerable, though they still amount to a few USD cents per kWh.: this adds significantly to the LCOE and is a disadvantage as compared to other renewable technologies such as PV and hydro [23]. This is especially so for offshore turbines, where costs can be double those onshore due to harsh sea conditions. Capital costs are dominated by turbine costs, which are in the range of 75–85 % as an approximate world average. And turbine costs in turn are heavily dependent on the prices of raw materials such as steel, copper, and cement. This makes it difficult to reduce turbine prices once maturity in their manufacturing has been achieved, since the final price depends more on the price of raw materials than on anything else. And since turbines account for the lion's share of the total cost of wind power systems the scope for further decreases in the price of turbines shrinks rapidly. In offshore systems the share of the total final cost accounted for by turbines is smaller (55–65 %), and cost reductions may come from other components in the system, e.g. connections to shore to deliver the power generated and connections to the general grid from that point, monitoring devices, and so on. It is difficult to envisage significant cost reductions in these items, nevertheless.

Wind farms have recently been deployed on a massive scale in some emerging economies, notably China and India. In fact, China stands today as the world leader in installed wind capacity. Turbine manufacturing costs in these countries are considerably lower than in advanced OECD economies, due to cheaper local labour and other conditions. Since the final turbines themselves are difficult to transport over long distances, market competition is unlikely to force costs to converge to the lowest possible values observed in these countries.

The history of costs reveals that they followed a continued decreasing trend from the beginning of significant deployment up to 2000–2004. Since then, that trend has ceased to exist, and prices even rose for a time before recently showing modests decreases again [40]. This is generally believed to be a sign that maturity in the manufacturing process has been achieved, and that the price increases observed were due to the increase in the price of raw material inputs, i.e. steel, copper and cement. Since that increase was probably due to the high growth rates of emerging economies, the current slowing in that growth rate may explain the decrease in the price of raw materials, and consequently of turbines. But this is all conjecture that may or may not be confirmed by future developments.

The technology of small sized turbines has only recently received any significant attention.[2] These turbines are frequently of the parallel rotating axis type, since they fit more easily into buildings and other small residential, commercial and industrial installations. They are a by-product of cost decreases in PV, which have opened up a new model for the process of generation/consumption of electricity: the distributed generation model. The small to medium consumer also becomes a producer, and small-scale wind technology becomes a natural complement to PV in this new model of electricity generation, distribution and consumption. Since they are at a very early stage of deployment, costs and prices are high compared to other wind and renewable technologies, but the turbines are obviously of the onshore type, which implies that their manufacturing process might benefit from all the advances already realised in the field of larger turbines.

A look at current costs and prices is in order at this point (see Tables 1 and 2). In future developments, costs may be expected to come down slightly, as with any other mature technology. Deployment will continue, and may take place at higher absolute rates, but it is likely that the fastest-growing renewable technologies will be solar, i.e. PV and CSP with TES, partly because they are less mature and partly because the prospects for cost decreases are significant. In Europe and other OECD countries, this growth may concentrate on offshore platforms in the North Sea, and mini-wind power to support PV deployment in the new model of distributed generation and consumption. This is also due to the fact that the best onshore sites are already taken. This new model (distributed generation and consumption of energy based mainly on PV and mini-wind power systems) is gathering support in many other parts of the world, but it must be pointed out that it is strongly opposed by traditional utilities, and to some extent also by governments. The final success and deployment of this technology thus hinges crucially on the result of that confrontation. In emerging and other non OECD economies with lower installed capacities, onshore developments will probably continue for a long while.

Competitiveness and grid parity, defined in one way or another, have already been achieved in a few cases and may be expected gradually to become the norm across technologies and countries. Moreover, and as noted for other renewables, as the share of production accounted for by renewables increases they will have to be looked at jointly, since synergies can be quite strong and can contribute significantly to ensuring security of supply, energy independence, network stability and cost competitiveness.

Summing up, wind power generation is a more mature technology than solar power. Any expected cost reductions are therefore likely to be modest, and costs might even increase, since turbine costs are highly dependent on the price of raw material inputs (mainly copper, steel, and cement). Offshore costs are considerably

[2] 'Small turbines' may mean turbines ranging in size from a few watts up to 100 kW or more, but there is no universally accepted definition.

higher but wind resources are also better, so the final LCOE is not substantially increased. Mini-wind turbines can be expected to be deployed jointly with PV solar technology in the new distributed power generation and consumption mode. In Europe and in OECD countries elsewhere, onshore resources are already exploited to a substantial extent, but offshore may be the next trend in windpower. In other emerging and less developed economies, the prospects for future deployments of both on- and offshore technologies are good.

3.4 Hydro Power

Hydro power is an old, mature, highly competitive renewable energy source with excellent properties and more installed capacity than any other renewable technology in the world. It is frequently the cheapest power generation technology, including all types of fossil-fuel sources [21]. There are three main types of plant: (1) reservoirs, which store water behind an artificial damn and enable power demand to be decoupled from energy storage: designs may range from small to very large, making this a highly scalable technology along the lines of PV; (2) "run of the river", with no storage; and (3) pumped storage, where water is pumped from a low reservoir to a higher one to be used for power generation at a later time. It is worth noting that it is usually electricity that is used to pump the water, so any energy source that generates electricity can be stored in this way (solar PV and wind power).

Since power consumption and energy storage are decoupled, the electricity is dispatchable at will. Moreover, because turbines can be ramped up and down almost instantly, it is dispatchable at all frequencies, from a fraction of a second to hours, with no significant extra costs, so it can offer all types of support to the electricity network, from ancillary services to all kind of reserves (spinning, operating, etc.). With pumped storage it can also provide greater dispatchability and back-up reserves for long periods of weeks, months and even years. Because of these properties, it is specially useful for balancing the intermittency of other renewables such as sun and wind energy. Thus, it acquires greater added value when the penetration rate of these energy sources is high.

Dispatchability means that there are two basic operating modes: (1) a continuous mode to meet base-load demand, implying high capacity factors close to 80–90 %; and (2) a peak demand mode, where the system is operated only at times when demand and prices are high, and obtains larger income in those periods. This implies lower capacity factors, typically in the range of 40–60 %. This mode allows for a smaller reservoir, so that up-front costs are also lower. Which of these designs (or any other in between) is preferred requires careful study in each specific case. Finally, depending on the specific design used, other non grid services may be offered such as flood and drought control, irrigation and potable water. Adding all of these up, a note of caution must be placed on the standard LCOE cost measure since, as noted in the discussion of CSP with storage, the total System LCOE (SLCOE) would be a better measure, even though it is more difficult to evaluate.

Up-front capital costs are high, and comprise the largest component of total costs: they include the power generating unit and civil work, i.e. the building of the dam itself and its associated components (penstock and racetail, possible access road and electricity lines to connect the system to the general grid). Table 2 offers some data drawn from a large sample of installations in operation around the world. The broad range of values reflects the disparity of local and project conditions, as noted. The price of 1 kW for large systems may run from a low of USD 1,050 to a high of 4,200 or, in some extreme cases, as much as 7,600. For small developments the range is similar, although the absolute values are slightly higher (1,300–5,000, and 8,000 in extreme cases). This also reflects the lack of sizeable economies of scale. It is noticeable that for developing countries smaller developments may even reach a low of USD 500/kW, which is indeed low, and may help off-grid electricity deployment with the help of other renewables such as solar, wind and biomass.

O&M costs, in contrast, make up only a small fraction of total costs. Project lead times are long (typically 7–8 years), which places strong constraints on the financing of projects (see, for example, [7]). This must be balanced against the long lifecycle of these systems, which can reach 70–90 years, with no need for significant refurbishment. This long life span also has a bearing on the calculation of LCOE. The standard discounting method makes all data beyond, say, 30–40 years basically irrelevant. Added to a potentially incorrect and overestimated discount rate, this may yield excessively high, incorrect LCOE values (see the Appendix for further discussion on this point). Table 1 presents recent estimates of LCOE from a large sample of working installations. The results can be remarkably low for small and large systems alike, depending presumably on the specific site, with figures as low as USD 0.02/Wh. But there is a broad range, as noted, and the figure can reach 0.13 for small designs (or even 0.27 for very small ones) and 0.19 for larger systems. There are many factors to be factored into the equation before a final verdict can be given on the profitability of any specific project, depending on specific and local conditions, as noted previously. Upgrading and refurbishing may be very low, from USD 0.01–0.05/Kwh. These low figures for upgrading must be assessed in conjunction with other potential environmental and social costs.

Because of local conditions at each specific site and other local costs, which may vary considerably, the price range of projects is broad, so additional care must be put into assessing the data presented in Tables 1 and 2 or in any other report. In fact, up to three quarters of the total investment costs, or even more, may be driven by site-specific conditions. Proper site selection and scheme design are therefore key issues, since they can avoid expensive mistakes [7]. It must also be remarked that economies of scale may be relevant at small sizes, say up to 50 or 100 kW, but are less so beyond that point [1]. There are no extensive data records available, so no learning rate can safely be estimated. But given the maturity of the technology, no significant cost reduction is expected; indeed, in many countries the contrary may occur, since the best sites are likely to have been developed already.

Some estimates [21] put the total world capacity still available at 5 times the existing installed capacity for large developments, and up to 20 times for small and medium systems [16]. This means a total of approximately 80 % of current energy consumption worldwide, and a much larger amount if only electricity is considered. This may be judgmental to some extent given that this value is quite difficult to estimate, but it is an indicator that substantial unexploited capacity still remains, and that sizeable future developments can therefore be expected.

Summarising, hydro power is an old, competitive, mature technology that has more installed capacity than any other renewable technology, though other technologies are being deployed at fast rates. At good sites, it is also the cheapest power generation technology, including all kind of fossil fuels. Moreover, it guarantees energy independence and security of supply. It has very good dispatchable capabilities at low or zero cost, and there is considerable capacity still available worldwide. It is an easily scalable technology, which makes it suitable for traditional centralised systems as well as for distributed generation and off-grid systems. Given all of these excellent properties and the large unexploited capacity still available around the world, substantial further deployment can be expected. Since the technology is already mature and competitive, no significant cost reductions are expected, and costs may even increase in countries where the best sites have already been exploited.

In spite of all these excellent properties, a word of caution must be said on the possible impact of climate change, given that changes in the weather and in other more permanent climate features may result in substantial decreases in rainfall, thus reducing water resources at previously good, developed sites [36]. This is an open question that will require close, careful attention in the near future.

3.5 Biomass Power

One of the main characteristics of biomass power generation is the large variety of power systems and fuel feedstocks that can be used as generating technologies. The costs and other relevant data therefore vary considerably, so there are no long historical series available for use in drawing conclusions on general patterns [19]. As of today, at least three technologies are mature and in some cases commercially competitive: stoker-boiler direct combustion (which accounts for 80–90 % of all systems worldwide); combined heat and power (CHP); and co-firing. Co-firing refers to the combination of biomass combustion with fuels of other types. This usually means coal or oil, though recently combination with CSP systems has been tried, thus increasing the dispatchable capabilities of that solar technology. Combined Heat and Power systems are especially useful at small to medium sizes, and may be a good support for the in-house power generation and consumption mode.

The variety of potential feedstocks is also large, which has a strong impact on the final competitiveness of the system. Perhaps the only general point about them is that they must be generated relatively near to combustion plants, since otherwise transportation costs make the system uneconomical. One important distinction is whether they come from waste materials of some type or from dedicated cultivated crops. The wastes used come mainly from three sources: agriculture, forestry and municipal solid waste. Being waste, they are available at little or no cost. The cost of dedicated crops is much higher, and the cost of oil must be singled out, since it is required to cultivate the crop itself and to transport it. This takes up resources that might otherwise be used in food production, which may further complicate this option. Accordingly, capital costs may have an impact on the final cost that ranges from 50–60 to 80–90 %, depending on the cost of the feedstock. The remaining costs are for O&M, which again may range from 5 to 20 % according to Irena [19].

Table 2 presents some data on capital costs for the main technologies that have reached maturity. For stoker-boiler combustion, which is the most common by far, the figure may be as low as USD 660/kW in developing countries with a high of 1,860, though this may reflect lower emission standards as well as other local costs, so the figure must be taken with care. In OECD countries standard values can be in the range of USD 1,880–4,260/kW. The costs of CHP technology are appreciably higher, but the difference must be weighted against the combined generation capacity of heat and power, so the final LCOE is not necessarily higher. The equipment required to add co-firing ability to existing systems is much less expensive, costing in the range of USD 140–850/kW, which may be especially significant for extending the dispatchability of CSP solar plants. The LCOE can be as low as USD 0.02/kWh on good sites, with a high of 0.06 (Table 1). These figures make the technology competitive in most situations. More typical figures lie in the range of USD 0.06–0.15/kWh, but systems may still be competitive depending on the local alternatives.

Combustion efficiency is generally in the range of 25–35 %, and capacity factors are usually high (80–90 %), provided feedstocks are available at all times, particularly all year round, which may not always be the case for agricultural and other wastes. One aspect of this technology that has not been sufficiently discussed to date is its dispatchability. This may become more significant in a future context of mass deployment of other intermittent renewable power sources (solar and wind). The two operating modes noted in the case of hydropower are available, i.e. continuous mode and peak demand load, and this also has an impact on the LCOE. Dispatchability is based on combustion technologies, so it may be more similar to the figure for gas fired plants than for hydro power. However such plants may still be quite relevant in the context of mass deployment of renewables, especially at local level. Capacity factors may also depend on the mode in which the system is operated, almost exactly as occurs with hydro power, i.e. continuous mode or peak load. In the latter mode capacity factors are lower, but the final LCOE may improve. Indeed, the very concept of LCOE is less applicable in these circumstances, as noted in the discussion of other dispatchable technologies, particularly hydro power and CSP with TES.

Given the low energy density of most types of feedstock, transport costs may have a strong impact on total cost. This means that the size of the combustion plant should be at most moderate, since the geographical radius of the collecting area cannot be too large. Consequently, economies of scale can only be obtained at low or very low levels. No significant improvements are expected in future costs for technologies that have already achieved maturity, such as biomass. There are, however, a large number of designs that are being researched at the pre-commercial level and in R&D laboratories that might in future reach the market and become competitive.

Given its dispatchability, the prospects for future deployment of the technology as a power generating source are good, especially as a support technology in the deployment and high penetration rates of other intermittent renewable power sources. The technology may also become an excellent support for the generated-distribution mode of production and consumption of electricity at local level, particularly when its heating capabilities are taken into account.

Summarising, there is a great diversity of biomass power techniques and feedstocks, but only three have reached maturity and commercial competitiveness: stoker-boiler combustion, CHP generation and co-firing. The first of these is by far the most common. The feedstock may be agricultural, forestry or municipal solid waste, or dedicated crops. In this last case the costs increase appreciably. In less developed countries costs can be very low, but this may mask less stringent controls on gas emissions. Biomass power generation is a dispatchable technology, which may make it especially attractive as a back-up and support at high penetration rates for other intermittent renewable power sources. Combined with heat generation, this enhances its potential for playing an important role in a context of increasingly high renewable penetration rates and a new mode of distributed generation and consumption of electricity at local level. All these factors make the future prospects for its deployment good.

3.6 Geothermal Power

The term “geothermal” is usually used to describe the energy stored close beneath the Earth’s surface (at depths of as far as 3,000 or 4,000 m) in the form of steam, hot rocks and superheated water (typically above 180°). There are two basic technologies for generating power: (a) ‘flashing’, based on steam or high temperature water converted into steam by dropping the pressure; and (b) “binary”, where the temperature is lower and some additional treatment is required to generate steam from a liquid at a low boiling point for subsequent use in a turbine. The latter is more expensive [18].

Finding a place with good resources is generally a costly, time consuming process. Once a site is found the costs of drilling equipment, the actual drilling of the production wells and other capital expenses related to the installation of the system are usually high. These initial costs are not expected to come down since this is a mature technology. Indeed, in the last decade they have risen around 60 % due to increased drilling activity searching for other fossil energy sources. Geothermal energy can still be quite competitive on good sites, although it is not generally available in significant amounts outside a few countries such as Iceland, Nicaragua, and the USA. Capital costs for 'flashing' type plants may range from USD 2,000–4,000/kW, whereas for 'binary cycle' plants the figure is slightly higher, ranging from USD 2,440–5,900/kW (Table 2). Standard LCOE values lie in the range of USD 0.09–0.14/kWh, and can be as low as USD 0.05/kW at good sites (Table 2) [17].

One problem with this technology is uncertainty as to its useful life cycle, which averages no more than 25 years in the best of cases, and as to the possible degradation of the quality of resources. This is a risk that adds to the capital cost, and given that the up-front investment takes the lion's share of all costs the final LCOE may increase significantly. This is a general problem with all renewable energy sources, except for biomass when feedstocks are not available at near zero cost. However, it is more significant in this case because of greater uncertainty. It must also be pointed out that this cannot strictly be considered as a renewable energy source, since the reservoirs have a limited life cycle. It is climate-friendly, though, since there are no emissions of polluting gasses.

These systems are usually operated in continuous time mode, and are therefore suitable for meeting base-load demand. But, at least in principle, there are no technical reasons to prevent them being used in other modes such as peak demand load, or even as back-up reserves. The potential pros and cons of these alternative modes would have to be carefully assessed though, since there is no prior practical experience.

Finally, the future prospects for deployment are not significant, partly due to the fact that the technology is quite mature already and no cost reductions can be expected, and also because there are better alternatives. This does not mean that the technology should be neglected, since it has some good properties that might become significant in the future.

3.7 Summary of Costs Data

In the Tables below, selected data are presented for the LCOE and total capital costs of the major renewable energies. These are the data discussed in detail in Sects. 3.1–3.6. The tables are based primarily on data provided by the Irena cost series [8, 18–23] but other less systematic sources and sources that rely more on estimations are also considered [29, 41]. The figures are weighted averages over different geographical areas. Thus specific values may fall outside the ranges presented. A comparative global assessment is needed at this stage. Such an assessment is presented in the next section.

4 Summary and Perspectives

However detailed and up-to-date a cost analysis may be, as presented in this chapter, it is at best nothing more than a snapshot of the current situation, with some hints as to the future. Nevertheless, an effort has been made to provide data and analysis that can provide insights into the future. This is very important in this field, since the accelerated deployment of renewable sources is bringing down their costs, and a host of new problems and possibilities are emerging (see, e.g., [35]). For instance, at world level half the new capacity additions to power generation are from renewable sources (in 2011: 41 GW wind, 30 GW PV, 25 Hydro and 6 GW biomass; [18]). The outlook for energy is shaped by three basic aspects: the huge, ever-increasing demand for energy, mainly from emerging economies; increasing difficulties to find accessible traditional fossil fuels; and the deployment of renewable sources. This last development has brought with it substantial cost reductions in energy sources of all types: hydro power, biomass and geothermal power are all competitive at market prices today in most situations. In fact, from a purely economic standpoint, renewables are already the default option for off-grid electrification and for virtually all electricity systems based mainly on diesel generation (for example, systems on islands and in remote locations).

The next question is whether further cost reductions can be expected, and if so which technologies look to be most promising. Some conclusions can be drawn straightforwardly from the presentation above: no significant cost reductions can be expected for hydro power, biomass or geothermal technologies; for onshore wind power cost reductions will depend strongly on future trends in commodity prices (steel, copper, cement), but the technology is near market competitiveness at good sites. Off-shore wind power is still too expensive, although cost reductions may be expected as its deployment continues. The outlook for cost decreases may be better in the case of mini-wind turbines, associated with in-house consumption and distributed generation, since they can exploit advances already available in onshore wind power generation. As for solar power, CSP solar tower technologies with thermal storage look promising for large plants from 100 MG to 1 GW and possibly more. They are not competitive yet, but further deployments could bring down installation BoS costs, even though no significant technical improvements are expected. Since this is a technology that is especially able to store energy in the form of heat, which can be quickly directed to generate steam and power, it may play an essential role in a complete renewables strategy. The last and most decisive analysis concerns PV solar technology: the costs of PV cells and modules have come down at an astonishing rate of 20–22 % per annum since records began in 1979, and the trend seems to have accelerated to 30 or 35 % in 2011–2012 [17, 25, 31].

This brought the cost of PV modules down to around USD 0.7/W by the end of 2012, and the share accounted for by the modules in the total final cost of a small to medium PV system to less than 50 %. Thus, even if module prices continue this trend, other installation costs will come to account for most of the total system cost, which means that the total final cost cannot be expected to decrease at such a high rate. Some further reductions in BoS costs can be expected as deployment continues and economies of scale come into play, but they are far more dependent on local conditions and not so exposed to competition forces. But even so, there is another crucial aspect that can and will come into play: technology improvements already achieved at R&D departments, some of which are almost ready for market deployment. Indeed, cell efficiency in commercial systems is close to 20 % in the best cases, but several research teams have announced increases to 40 % or more. And for one type of cell, the Concentrated Power PV, efficiency might reach close to 90 % [22]. This last development is not expected to be available on the market soon, but it is a clear indication that the LCOE of the PV power might decrease fourfold in the near future.

If all these trends continue, PV solar can be expected to become the most cost effective of all renewable technologies, and indeed of all energy sources of any kind, including fossil fuels. At sites with sufficient direct or even diffuse solar irradiance, it is set to become the dominant power source: not just another form of energy, but 'the' energy as some authors put it several decades ago and have reminded us lately [37]. However, one difficulty remains with it: storage to make up for its variability. But this can be solved by the joint development of other renewable technologies such as wind, hydro power with storage, biomass and CSP with TES in utility scale installations. There is currently not much research ongoing on this topic, but it could bring about a further revolution in solar PV applicability. The learning rates given for PV technology costs and the efficiency improvements achieved apply equally to both c-Si and CdTe cells, and since the latter are especially suitable for many building applications, increasing BIPV applications can also be expected.

Sometimes it is also argued that another general push to cost reduction across the board might come from emerging economies, mainly China and India, where total costs for all technologies are generally lower than in more advanced countries. But that has to be balanced against the permanently depreciated exchange rate of the Chinese currency, which implies lower international prices for their products and thus increased exports. Moreover, general labour costs are very low compared to European and other developed nations, but that is also likely to change as middle classes achieve acceptable welfare levels.

Summing up, significant cost reductions in CSP and wind technologies can be expected, along with quite marked decreases in costs and increases in efficiency in PV systems. The remaining technologies— hydro power, biomass and geothermal—are already mature and competitive, and no significant changes are to be expected in them. Table 3 offers projections for capital costs and the LCOE in 2,020 of renewable technologies that have not yet achieved maturity but are expected to do so sometime in the near future. It is of interest to note that in some cases -notably PV- reality has already outdone these forecasts. This has happened quite frequently in recent experience with rapidly evolving technologies, as is the case with renewables [31].

Although this is the likely outcome, risks remain in the outlook for competitiveness of renewables because the price of some commodities such as cement and steel, which serve as raw inputs for wind turbines, may increase, and the price of fossil fuels may fall. However, as noted above, this last development is unlikely in

Table 3 Renewable technologies

	Lcoe		Capital costs	
	2012	2020	2012	2020
Wind				
Onshore	0.06–0.14	0.04–0.13	1,750	1,350–1,450
Offshore	0.15–0.23	0.15–0.19		
PV				
Utility scale/grid	0.13–0.31	0.09–0.36		0.4–0.5 (modules)
CSP				
(Solar tower)	0.17–0.29	0.12–0.16		28 %[a]
Parabolic troughs				17–40 %
No storage	0.18–0.38	0.16–0.28		
Storage (6–15 h.)	0.17–0.26	0.11–0.14		

[a] Percentage reduction
LCOE in USD/kWh; Capital costs in USD/kW

view of strongly increasing demand for energy in emerging economies: indeed, only if this increased demand is met to a large extent by renewables might fossil fuel prices stop increasing. And fossil fuels are also increasingly risky and costlier to discover and exploit, prone to accidents and requiring costly insurance policies.

The next logical question is how these cost reductions are going to modify the energy outlook, if at all, since the scope of economically viable applications for renewables will increase even further. Note first that solar PV, biomass, hydro power and wind are highly modular, scalable energy sources which can be combined into mini-networks to electrify isolated communities and to expand the existing network. The complementarity of the different renewable energy sources, combined with small hydro plants with reservoirs for water storage or other energy storage options can help eliminate the final variability in the electricity supply and offer complete low-cost electrification alternatives. Thus, renewable energy seems set to become a game-changer, and within it solar PV is set to be a further game-changer. In view of this, policy-makers will soon have to shift from specific support packages for each technology to packages designed to minimise the total costs of the electricity system with higher levels of intermittent renewable energy. In fact this is already the trend in the market, which is set to reduce its dependency on political support sooner rather than later.

One interesting way of trying to figure out how all this may impact the energy outlook is to look at the survey conducted by a consultancy company [34] on the CEO's of several energy companies around the world. The following general conclusions can be drawn, although with different levels of agreement: (1) there is almost complete agreement that the power utility business model is set to be completely transformed or undergo important changes; (2) more than half the respondents say that distributed generation will force utilities to change their business model, and there is also general agreement that the centralised generation and distribution model is going to lose its lead role; (3) however, more than 80 % consider distributed generation as an opportunity rather than a threat; and (4) many also expect an important role to be played by unconventional energy sources, such as shale and oil gas. However, there is a general concern about their negative impacts on society, and agreement on the benefits of renewable energy, which is considered to be here to stay.

It is also realistic to expect these changes to be implemented more rapidly in emerging economies with less well developed grids and high demands for energy. OECD and other developed countries, by contrast, are organised around the centralised system of generation and distribution for energy, and will put up more resistence to changing the model. Non economic barriers of all kinds to the deployment of renewables and the change of model are to be expected (administrative, political, etc.). A case in point might be precisely Europe, where the current crisis is being used as an argument to set up barriers to renewables, which supporters of renewables would portray as just an excuse.

Although this final reflection lies somewhat beyond the scope of this chapter, it is worth noting that a world of energy abundance is likely to become a reality in two or three decades, with fossil fuels having a more or less significant share: in other words, the energy problem might be solved. But it cannot be forgotten that increasing demand for all resources, notably food and water in the near future, in an inevitably finite world, cannot be sustained forever. That is, even if the energy problem is overcome it may be time to stop looking only to real growth, as measured by the standard system of national accounts, and broaden our perspective of welfare to one of ‘prosperity’ [24].

Appendix

A.1 The Meaning and Calculation of the LCOE Cost Measure

This appendix seeks to shed some light on the advantages, pitfalls, and precise meaning of the electricity cost measure provided by the Levelised Cost of Energy, or LCOE, sometimes also abbreviated to LCE. Standard cost measures are needed that everybody can easily understand so that the relative costs of different technologies and investments can be communicated and assessed. The measure is perfectly valid, once it is established precisely what it means and what it does not mean. There are other accepted, standard measures, most notably the cost of the kW for a given technology, that enable the initial capital investment required in a specific project to be calculated. This is clearly also relevant, since the amount of resources required to finance a project, independently of its expected rate of return, may be a serious hurdle if it is large (e.g. nuclear or large hydroelectric dams).

The LCOE, by contrast, is intended to provide a measure of cost that can be compared with the selling price of electricity for a given project, that is, its competitiveness. This measure is highly dependent on several factors, including the specific country and geographical site, and on the type of technology and subtechnology within the relevant category: it is very different for rooftop FV and large utility-scale ground-mounted installations, for example. The specific country may have an impact on costs of deployment, labour costs, degree of market competition and other factors that are directly linked to the profit margins of suppliers, and so on. Sites affect mostly the capacity factor, i.e. the amount of time within a given period, usually one calendar year, that a plant will be working and producing electricity. For example, the number of effective sun hours for solar energy, and hours of wind for windpower, suitably weighted for 'intensity' in both cases (speed in the case of wind and irradiance for solar).

The LCOE can be defined generally as the discounted lifetime cost divided by the discounted lifetime generation. It is therefore expressed as a monetary value for a certain specified amount of energy generated during a specified period (e.g. USD/MWh). It is intended to represent the total life-cycle costs of producing one MWh of power using a specific technology. Another more meaningful way to define the LCOE is as the price of electricity required for a project to yield revenues equal to its costs, including a return on the capital invested, i.e. to break even. A higher electricity price would yield a greater return on capital, while a lower price would yield a lower return on capital, or even a loss, i.e. the value at which one particular investment breaks even or equals the current selling price of electricity. This point is frequently referred to as 'grid-parity', or the moment and cost at which the specified technology becomes competitive at a given site, i.e. needs no further financial support from the state or elsewhere. This way of looking at matters enables certain concepts to be discussed, notably the discount rate that should be applied, the possible inflation rate and other forecasts for future trends in the monetary magnitudes that appear in the definition.

The specific expression for calculating the LCOE of an energy investment is given by

$$\text{LCOE} = \frac{\sum_{t=1}^{t=n}\left(\frac{I_t+\text{O\&M}_t+F_t}{(1+d)^t}\right)}{\sum_{t=1}^{t=n}\left(\frac{E_t}{(1+d)^t}\right)}$$

where

I_t represents the capital cost expenditures in year t
$O\&M_t$ is the operating and management costs in year t
F_t is the cost of fuel in year t
E_t is the amount of energy generated in year t
d is the discount rate
n, is the expected lifetime of the investment

The time unit usually taken for renewables is one calendar year, since over that period the natural cycle of resources will usually be repeated, to some extent, but this is arbitrary. The cost of fuel, F_t, is zero for most renewables energies, except in the case of biomass. The capital cost includes all forms of financing that may be involved, possibly including equity. The return on capital applied to each category of financial source may be different, and will include a risk premium. In the case of equity, this premium will usually be higher. The return on capital applied in the calculation of LCOE is usually a Weighted Average Cost of Capital or WACC. The LCOE therefore includes a positive return on equity if any. It can be understood as an opportunity cost, so that the current return on capital in the relevant market and an appropriate risk premium are taken into account. This is the most commonly accepted definition [18, 29, 41], though there may be some minor changes in some cases (the EIA follows a slightly different approach: see [8]).

The concept of LCOE deserves some discussion in order to provide a better understanding of its meaning. It can be written in a compact way as follows:

$$\mathrm{LCOE} = \frac{\mathrm{DLC}}{\mathrm{DLG}}$$

where the numerator is the discounted lifetime cost (DLC) and the denominator the discounted lifetime generation (DLG). Now rewrite this last expression in the following way:

$$\mathrm{LCOE} \times \mathrm{DLG} - \mathrm{DLC} = 0$$

If the LCOE is now replaced by the current selling price of energy, PE, the following is obtained:

$$\mathrm{PE} \times \mathrm{DLG} - \mathrm{DLC} \geq 0$$

when the selling price is above the LCOE (PE > LCOE). This implies that the investment will yield a greater return on capital than the ‘normal’ or current market return, and a lower return if it is lower. If the two are equal the ‘excess return’ is zero and the investment breaks even (‘excess’ here means ‘above what is taken as standard in the market’). This point is what is commonly referred to as ‘grid-parity’, a time and amount at which the specific technology considered reaches market competitiveness, and therefore requires no further public (financial) support in any form. It may require other kinds of support, however, in the form of easing administrative barriers, or otherwise.

Another point that has been brought to the discussion recently is the very concept of an electricity price. This may be unfair to technologies with storage capacities, since they can sell electricity at different times, taking advantage of the changing prices of electricity over time (e.g. hydro power with pumped storage and CSP with TES in molten salts). Indeed, this applies to all technologies with intermittent or non constant output, i.e. all renewable technologies to a greater or lesser degree. This point deserves some discussion: consider the present discounted value of all future energy proceeds, DLP for short, generated by a specific investment and given by

$$\text{DLP} = \sum_{t=1}^{t=n} \left(\frac{P_t \times E_t}{(1+d)^t} \right)$$

where P_t is the selling price of electricity at a specified future time t (the remaining symbols are defined above in the expression for the LCOE). Now denote $D_t = (1/(1 + d)^t)$. For ease of notation, this expression can be conveniently rearranged as follows:

$$\begin{aligned} \text{DLP} &= \sum_{t=1}^{t=n} P_t \times E_t \times D_t \\ &= \left(\sum_{t=1}^{t=n} E_t \times D_t \right) \times \left(\sum_{t=1}^{t=n} P_t \times \left(\frac{E_t \times D_t}{\sum_1^n E_t \times D_t} \right) \right) \end{aligned}$$

The first summation term in brackets is precisely the present discounted amount of all energy generated in the future, i.e. the denominator in the standard definition of LCOE; the second is a weighted average of all future electricity prices, where the weights themselves are discounted to the present. A very similar distinction is made in finance: see, for example, Bierwag [2]. Finally, this weighted price is what should be compared to the LCOE in order to arrive at a meaningful conclusion, rather than to an abstract concept of "electricity price" which in practice is rarely a constant value.

In practice, the concept of LCOE is used with no in-depth consideration of its many underpinnings. A thorough discussion of all those underpinnings is beyond the scope of this chapter, but some mention, however preliminary, should be made of them. A brief comment on some of the main points follows: (1) the price P_t, and the electricity E_t, both refer to a future calendar year, and both will change over time; even within a given year the price changes hour by hour. Thus, the method for forecasting P_t, and E_t, will have an impact on the final calculation; (2) a context of likely increases in the prices of non renewables should be considered when calculating the LCOE for these technologies; (3) calculations are customarily performed assuming constant prices (one exception is [41]); however, even if inflation rates are low, for long time frames they may be relevant, so they should be dealt with appropriately; (4) the discount rate may have a strong impact on the final calculated value; Irena, for example, uses the WACC, which is 10 % in their case; a study conducted on behalf of the British Government recommends using a 3.5 % discount rate [38], finally, [9] suggests a declining discount rate, since otherwise future distant revenues will play no role; (5) when making international comparisons, the choice of the conversion rate is another factor that may have a decisive impact on the final assessment. A discussion of this point can be found in [30];

(6) the value assigned to the average cost of capital, or WACC, is more relevant in the case of renewable energies, since capital costs are the largest fraction of all costs and therefore have a strong impact on the calculated value for LCOE. A common value assumed in many reports is 10 % [18, 29, 41]; (7) whether the cost is measured from the point of view of a producer-investor or a consumer is another relevant point. In the latter case the price paid by consumers may be as much as four times higher than the price obtained by an investor who sells directly to the grid. Note also in passing that this distinction is also crucial when discussing the concept of 'grid-parity'.

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Interactions Between Climate Policies in the Power Sector

Paulina Beato and Juan Delgado

Abstract For the purpose of limiting global temperature increases, governments have designed a broad range of policy instruments in order to reduce carbon emissions such as carbon taxes, carbon markets and renewable energy support policies. Although such instruments aim to serve the same purpose, they are rarely fine-tuned to guarantee their consistency. Carbon markets are in theory the most efficient instrument to reduce emissions. The use of other instruments is justified under the presence of circumstances that undermine the effectiveness of carbon markets such as market design flaws or innovation externalities. In such cases, the optimal climate policy mix should be carefully designed to take into account the potential interactions between policy instruments.

1 Introduction

In the context of the United Nations Framework Convention on Climate Change, countries have agreed that greenhouse gas (GHG) emissions need to be reduced so that global temperature increases are limited to below 2 °C.

For that purpose governments all over the world have designed a broad range of instruments in order to reduce carbon emissions and consequently limit the global temperature increase (in addition to mitigation measures addressed to reduce the

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impact of climate change). Such measures include carbon taxes, carbon markets, subsidies to renewable sources of energy, subsidies to R&D and energy efficiency measures. Often they have set different targets for different instruments such as the European 20/20/20 setting targets for emissions reduction, renewables and energy efficiency.

Instruments and targets might complement each other but often their interaction might lead to lower effectiveness and higher costs for reducing emissions. This is the case when instruments and targets are not set and designed consistently. For example, measures adopted to meet a potential renewables target will affect the emissions price reducing the effectiveness of carbon policies. If such measures imply the funding of expensive or ineffective technologies, the final outcome will be suboptimal (since other more efficient ways to reduce carbon emissions might be displaced).

The design of optimal climate policies should bear in mind the goals pursued, whether the proposed instruments are appropriate to meet such goals and whether the interactions between objectives and instruments might reduce the effectiveness of the policy mix.

The optimal policy mix should guarantee the effectiveness in meeting its ultimate goal, e.g. the reduction of emissions, in the most efficient way.

The power sector in the European Union is a good illustration of the coexistence of several climate policy instruments and targets: The power sector takes part in the European Emissions Trading Scheme (ETS) carbon market and thus generators need to hold permits in order to be able to emit GHG gasses. In addition, most EU countries have in place support mechanisms for the deployment of Renewable Sources of Energy for Electricity (RES-E) either though Feed-In Tariff (FIT) systems or Tradable Green Certificates (TGC) in order to meet their assigned RES-E quota.

Under some circumstances, the coexistence of several policy instruments can make sense from an efficiency perspective: for example, RES-E support mechanisms might complement the carbon market if, due to the existence of market failures or design flaws, this does not function properly. Also, in the presence of innovation externalities, promoting the deployment of RES-E (if such externalities arise from learning by doing) or funding R&D in RES-E or carbon efficient technologies (if such externalities arise from R&D-driven innovation) might help to increase innovation and reduce the carbon abatement cost, accelerating the decarbonisation path.

In summary, in order to be effective, the policy mix should be carefully designed: first, additional instruments should respond to market failures and, second, the potential interactions between policies should be internalised in the design of additional instruments to guarantee the minimal distortions across instruments.

This chapter analyses the coexistence of policy instruments to fight climate change and the interactions between them with a focus in the power sector. In particular, the chapter first reviews the empirical evidence on the impact of the coexistence of several climate policy instruments in the power sector and then, through the use of a simple theoretical model, analyses when it is justified the use of several instruments and how such instruments should be designed. It is assumed that carbon abatement is the only objective of climate policies. Other objectives such as job creation, industrial policy related goals or energy independence are not included in the analysis.

The chapter is organized as follows. Section 2 briefly presents the potential contradictions and deficiencies of the current EU climate policy framework as an illustration of the poor coordination of multiple instruments. Section 3 reviews some empirical evidence on the interaction of several policy instruments and the implications for carbon prices, power prices and the policy costs. Section 4 presents a simple theoretical model that will be used to analyse different policy scenarios where additional policies might be used. Section 5 analyses, using the theoretical model, how different market imperfections and failures can be internalised in the design of optimal policies. Section 6 concludes with policy recommendations.

2 Interaction Between Policy Instruments: The Case of EU Climate Policies

The European Commission (EC) recently announced the EU climate objectives for 2030: A reduction in GHG emissions by 40 % below the 1990 level and an EU-wide binding target for renewable energy of at least 27 %.[1] The new 2030 targets are a continuation of the ambitious 20/20/20 plan launched by the EC in 2009.[2]

The EU climate policy route is an example of multiple non-consistent targets and instruments. Such inconsistency comes from two sources: first, from the lack of evidence on the complementarity between the different targets and between the different instruments and, second, from the different geographic dimension of the policy instruments, which combine Europe-wide instruments such as the ETS with domestic policies such RES-E support mechanisms without explicit coordination mechanisms across member states.[3]

The EU framework sets a target for GHG emission reduction and national quotas for renewables. The ETS is the most ambitious instrument to reduce emissions. It consists of a cap-and-trade scheme that covers almost 50 % of EU GHG emissions. In addition to the ETS, there is a range of mostly domestic measures designed to reduce emissions in sectors not covered by the ETS.

The attainment of the renewables target has been mostly delegated to national governments. Each member state is free to design the necessary instruments to meet its domestic target. In particular, in the power sector two RES-E support

[1] See IP/14/54 (22/01/2014): "2030 climate and energy goals for a competitive, secure and low-carbon EU economy" available at http://europa.eu/rapid/press-release_IP-14-54_en.htm.

[2] The Climate and Energy Package set the guiding principles for the EU climate policy until 2020: a 20 % reduction in greenhouse gas emissions from 1990 levels, an increase of the share of EU energy consumption produced from renewable resources to 20 % and a 20 % improvement in the EU's energy efficiency.

[3] Batlle et al. [2] provide a comprehensive review of the interactions between EU climate policy instruments in the power sector.

instruments have been widely used to promote the deployment of renewable energies: TGCs which are based on an obligation to produce a certain amount of renewable energy (a certificate is created per unit of renewable energy produced) and direct subsidies per unit of renewable energy produced or FITs, which constitute direct subsidies to the production of RES-E.

The ETS is the central piece of EU climate policies. The ETS allows flexibility to reduce carbon emissions across sectors without prescribing a specific technology. However, the ETS has proved not to be that effective because of design issues and the lack of predictability.

Additional policy instruments and targets, such as RES-E support mechanisms, seem to compensate the lack of confidence on the ETS. However, there is no evidence that such targets have been set consistently with the GHG emission reduction targets.[4] Moreover, the fact that RES-E support policies are designed at national level does not guarantee their consistency across countries. Also, there is no evidence that governments have considered the interaction between their national policies and the EU ETS when designing them. This has resulted, on the one hand, in overinvestment in some technologies such as solar photovoltaic in Spain and Germany and, on the other hand, a poor performance of the ETS.

There have been several factors that have affected the functioning of the ETS and that might justify the use of additional instruments:

First, the excessive number of emission permits has made the ETS ineffective. Companies have received a large amount of permits to pollute limiting its obligations to reduce their carbon emissions. The excess of emission permits has been estimated on an overall surplus of 267 $MtCO_2e$ in the first phase (2005–2007)[5] and 970 $MtCO_2e$ in the second phase (2008–2012).[6] The excessive number of permits leads to lower carbon prices and a poor performance of the ETS.

Second, the systematic free allocation of permits resulted in "windfall profits" for the industry. Economic theory suggests that companies will partially pass through the costs of the freely obtained permits and that has been proven the case with the free permits allocated on energy-intensive industries. Bruyn et al. [8] show that carbon prices have a significant influence on several product prices, and estimated that windfall profits in the refineries, iron and steel and chemical sectors accounted for 14 billion of euros during the period 2005–2008.

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4 In fact, according to the Commission impact analysis of the 2009 Climate Package (ANNEX TO THE IMPACT ASSESSMENT. Document accompanying the Package of Implementation measures for the EU objectives on climate change and renewable energy for 2020, p. 34), meeting the GHG reduction target would only require 15.8 % of renewables in total energy consumption. This implies that the remaining 4.2 % increased the cost of reducing emissions and, thus, did not constitute a cost efficient way to reduce GHG emissions. The Commission naively stated that putting a renewables policy in place would lower the carbon price necessary to deliver the GHG reduction commitment from €49/tCO_2 to €39/tCO_2 but did not evaluate the total cost of meeting the GHG target under the different scenarios.

5 CTW [9].

6 Kossoy and Ambrosi [19].

Third, the existence of high price volatility could have discouraged investment in low carbon technologies and undermined carbon reduction objectives. High volatility has been present in the market since its creation. For instance, prices remained around 26€ from January until the end of April 2006, but dropped to around 10€ as response to the publication of verified data for 2005.[7]

Fourth, the ambitious renewables target and the generosity of some national schemes have had a negative impact on the price of carbon, reducing the effectiveness of the ETS.

Finally, the economic crisis has reduced the economic activity and thus the demand for carbon permits which has resulted in important reductions on the permit's price. Prices decreased to 10.15 in 2009 compared to 30 in July 2008.[8] Recently, prices have been consistently around 5€. In response to this, the European Union recently approved a "back-loading" plan that aimed to boost the flagging price of carbon by removing carbon permits from the market.

The lack of effectiveness of the European carbon market has taken some authors to claim for the use of additional instruments. However, in some cases, like in the case of RES-E support mechanisms, such instruments have contributed negatively to the effectiveness of carbon markets.

The next section reviews some empirical evidence on the interaction of climate policies and the impact on carbon prices, power prices and the cost of policies. The object is to illustrate how a wrong policy mix can distort carbon and power markets and reduce welfare.

3 Interaction Between Policy Instruments: Empirical Evidence

The quantitative evaluation of the impact of the interaction between policies requires the simulation of the power industry under different policy scenarios. The exercise is not absent of complexity given the combination of supranational and domestic policies, the long term-nature of climate policies and the complex interaction between the different policies makes the exercise rather complex. The current section reviews some of the existing evidence on the quantification of policy interactions. Such evaluation is made through sophisticated partial equilibrium models of the power sector[9] or through he simulation of stylized models.[10]

[7] Betz [3].

[8] Morris and Worthington [23].

[9] For example, the TIMES-D model used by Götz et al. [15] which is based on the model generator TIMES, which has been developed in the scope of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA), or the MARKAL model used by Unger and Ahlgren [24].

[10] For example, Fischer and Newell [11].

In particular, the review focuses on the comparison of scenarios where only a carbon price instrument is used with scenarios where a carbon price is combined with RES-E support mechanisms. The comparison across studies is not feasible given the different assumptions and parameters.[11] However, it is possible to extract some general conclusions: first, the empirical evidence shows that the impact of RES-E support policies on the price of carbon is substantial and extreme cases might drive the carbon price close to zero, making the ETS a superfluous instrument; second, RES-E support mechanisms lower the wholesale power price but, if they are financed through an uplift on final consumers, they might end up increasing electricity retail prices; and finally, RES-E support mechanisms are an expensive policy instrument that increases the abatement costs and reduces welfare. Table 1 in the annex summarises the main results.

3.1 Impact on Carbon Prices

Practically all the studies analysed conclude that the combination of carbon markets and renewable support mechanisms reduce the carbon price. The existence of RES-E support mechanisms creates incentives to invest in renewable energy and reduces the demand for carbon certificates. This makes the carbon market constraint less binding and therefore the permit price lower. As pointed by De Jonghe et al. [10], for a relatively high quota of renewables, the carbon allowance price is more dependent on the quota than on the carbon restriction. In the extreme case, for a sufficiently high renewables quota, the carbon price can be close to zero.[12]

The impact on carbon prices of policies based on renewable targets varies substantially from case to case but they imply in most cases price reductions above 50 %.

3.2 Impact on Electricity Prices

The impact of combining policy instruments on retail electricity prices varies substantially from case to case. There are several issues at stake that may have opposite impacts: on the one hand, the increase in the renewables quota reduces the carbon price and will therefore tend to reduce power prices. Also, since the production of renewable energy usually will enter the spot market at a price close to zero, the

[11] The comparison of the results of the different analysis is complex given the large number of scenarios and parameters involved, the different assumptions, targets and diverse geographical coverage and the timeframe of the different exercises. The analysis at national level requires for example strong simplifying assumptions regarding the existing interferences in other countries.

[12] Abrell and Weigt [1] reach this result for a quota of 20 %. However, their results seem too low as compared to Götz et al. [15].

Table 1 Evidence on interaction between climate policies

		Scenarios			Impact		
Study	Country	CO_2 target	RES-E target	Instrument	CO_2 price €/ tCO_2	Retail power prices (% change with reference to no policies * or to carbon price only**)	Policy costs
Götz et al. [15]	Germany	21%	–	TEP	19.10	–	FIT additional costs rise strongly until 2020 up to 15 billion € per year and then drop substantially until 2030 as renewables become competitive. Even though the FIT system has the dampening effect on ETS certificate prices, the additional cost burden of this support scheme leaves to a rise in energy system costs in Germany with a cumulated difference for the time period of 2015–2030 of 7.3 billion € per year
		21%	No explicit target	TEP +FIT	14	6.3 %**	
Abrell and Weigt [1]	Germany	20 %	–	TEP	3.43	2.16 %*	Renewable policies lead to a higher welfare loss than the pure reduction scenario (−0.019 %) since electricity producers deviate from their cost minimizing generation portfolio. This effect is only slightly more negative for the case of differentiated feed in tariffs (−0.0194 %)
		20 %	20 %	TEP + TGCs	0	1.11 %*	
		20 %	20 %	TEP+FIT	0	1.12 %*	
Böhringer and Rosendah [l5]	Germany	25%	–	TEP	20	12 %*	The compliance cost of reaching an emission target increases with the stringency of the emission target, but also with the green quota. That is, there is significant excess cost of introducing a binding green quota on the top of the emission constraint if the only goal is to reduce emissions of CO_2.
		25 %	23 %	TEP +TGCs	8	4 %*	

(continued)

Table 1 (continued)

		Scenarios			Impact		
Study	Country	CO_2 target	RES-E target	Instrument	CO_2 price €/ tCO_2	Retail power prices (% change with reference to no policies * or to carbon price only**)	Policy costs
Unger and Ahlgren [24]	Nordic countries	30 %	10 %	TEP + TGCs	14	0 %**	The reduction in CO_2 emissions due to a TGC system including a quota of only 10 % is seven times more costly than a TEP system with the same CO_2 reduction over time. The cost difference is at its minimum, i.e. roughly 3 times, at a TGC quota of approximately 30 %. For higher TGC quotas than that, there is hardly any further reduction in CO_2 emissions from the TGC system since all electricity supply is virtually emission-free
		30 %	20 %	TEP + TGCs	6	−3.22 %**	
Hindsberger et al. [16]	Baltic region	55.9 Mt CO2	-	TEP	18	14.49 % (Spot prices)	
		55.9 Mt CO2	23.60 %	TEP +TGCs	7.50 €	−3.42 % (Spot prices)	
De Jonghe et al. [10]	Benelux	20%	-	TEP	20	25 %*	
		-	20 %	TGCs	-	17.5 %*	
	France	20 %	-	TEP	20	0 %*	
		-	20 %	TGCs	-	17.5 %*	
	Germany	-	-	TEP	20	40 %*	
		20 %	20 %	TGCs	-	17.5 %*	

(continued)

Table 1 (continued)

		Scenarios			Impact		
Study	Country	CO_2 target	RES-E target	Instrument	CO_2 price €/ tCO_2	Retail power prices (% change with reference to no policies * or to carbon price only**)	Policy costs
Linares et al. [21]	Spain	30 %	-	TEP	22.05	34.91%*(Wholesale)	The combination of instruments features higher costs, although it shows some synergies: the simultaneous achievement of the emissions reductions and high penetration of renewable energies only increases costs by 3 % with respect to the emissions trading system only.
		30 %	17.5 %	TEP+RPS	14.71	32.04 %*(Wholesale)	
Fischer and Newell [11]	US	4.8 %	-	TEP	-	−2.2 %*	The most efficient policy is the emissions price, leading to the least cost in terms of surplus. The emissions performance standard is the second most cost-effective instrument, reaching costs 41 % higher than the emissions price. The other policies can be described as offering different combinations of these incentives, which have different consequences for the distribution and the over all size of the burden of meeting an emissions reduction target.
		4.8 %	-	Emission Price	$7	5 %*	
		4.8 %	-	RPS	-	−0.9 %*	

(continued)

Table 1 (continued)

		Scenarios			Impact		
Study	Country	CO_2 target	RES-E target	Instrument	CO_2 price €/ tCO_2	Retail power prices (% change with reference to no policies * or to carbon price only**)	Policy costs
Morris et a.l [22]	US	80.0 %	-	TEP	$235	-	There is a negative effect on welfare related to the introduction of RPS policy. Specifically, the effect of adding a 20 % RPS requirement to the existent cap-and-trade policy, implies a loss of 1.50% in terms of welfare for the year 2030, and −2.3 % for the year 2050.
		80 %	20 %	TEP + RPS	$191	-	

FIT: Feed-in Tariff, TEP: Tradable Emission Permits, RPS: Renewable Portfolio Standard, TGCs: Tradable Green Certificates wholesale electricity price will decrease. On the other hand, if costs of FITs or TGCs are recouped via uplifts on electricity retail prices, then they will contribute to increase retail prices. Therefore, the final impact on electricity prices is uncertain. However, if the costs of supporting RES-E are funded via any other source, then the impact of combining both instruments will be a reduction of retail power prices.

In summary, it can be expected that for a high renewables quota, retail electricity prices will normally increase since the volume of subsidies will be larger than the wholesale savings. While for a low renewables quota or for cost of renewable funded out of consumer prices, the wholesale savings effect might dominate and the retail price might decrease.

The empirical findings illustrate these effects. For example, in Unger and Ahlgren [24] the wholesale price is decreasing on the renewables quota. However, the retail price decreases for a quota below 25 % and increases from there on. Notice that as soon as the FIT or TGC required for a specific target becomes positive, then the policy costs of renewables increases rapidly since subsidies are normally paid also to all renewable production, even to the energy that would be produced in the absence of a RES-E support scheme.

The net impact of the combined policies also depends very much on the energy mix. For example, as shown by De Jonghe et al. [10], France has a relatively carbon-free energy mix so the imposition of a carbon price will practically not affect the electricity prices but the imposition of a renewables quota will do. On the contrary, for Germany and the Benelux they show that the imposition of a 20 % renewables quota will reduce the retail price (if FITs are optimally set). Finally, Götz et al. [15] show that if the quota reaches 40 %, then, the impact on retail electricity prices will be positive.

3.3 *Cost of the Policies*

All the studies analysed conclude, as expected, that the most efficient policy in terms of cost or welfare is the use of tradable emission permits. The additional policies, since they imply a bias towards specific technologies which are not necessarily the most efficient, lead to higher policy costs. In particular, the establishment of a RES-E support mechanism generally leads to higher costs. Unger and Ahlgren [24] show, for example, that the reduction in carbon emissions due to a TGC system including a quota of only 10 % is seven times more costly than a TEP system with the same carbon emission reductions over time. The cost difference is not however monotonic: it is minimal for a quota of 30 % (3 times) and beyond that there is hardly any impact on carbon emission reductions (since all energy would be produced from renewables, hydro and nuclear).

Böhringer and Rosendahl [5] estimate that the compliance cost of reaching a 25 % carbon emission reduction in Germany is twice as high with a green quota than in the absence of it (2200 million Euros vs. 1100 million Euros). Compliance costs double when there is an increase of 10 % in the renewables penetration.

4 Climate Policy Instruments: A Simple Model

We develop a simple theoretical stylized model to analyse the interaction between the different policies in the power sector and the implications for policy design. We focus on the electricity sector that amounts for close to 40 % of the emissions of the economy and where emissions reduction policies and renewables polices concur. The model is deliberately kept simple to identify the key features of the arguments (a more comprehensive stylized model can be found in [11, 12].

4.1 Supply and Demand

Assume there is a monopolist that produces electricity using two technologies: a fossil-fuelled technology and a renewable technology.

The cost of producing q_1 units with the fossil-fuelled technology is $c_1(q_1)$. The conventional technology emits $e_1 = f(q_1)$ carbon units when producing q_1, where $f'(q_1) > 0$.

The cost of producing q_2 units with the renewable technology is $c_2(q_2)$, where $c'_2(q) > c'_1(q)$ for all q,[13] the associated emissions e_2 are zero.

Assume the inverse demand for electricity is P(Q) where Q is the quantity demanded and P is the price for electricity. Renewable energy and fossil-fuelled generation are assumed to be perfect substitutes.

4.2 Policies

We initially consider two policies: a renewables subsidy and a carbon market. The renewables policy consists of a subsidy r per unit of electricity produced from renewable sources up to a target R. The carbon market consists of a cap E on the total carbon emissions of the economy and tradable certificates which are priced according to supply and demand. Carbon emissions of the rest of the economy are a function of the carbon price, p_e, and are determined by the equation

$$e(p_e) = H - hp_e$$

[13] Strict marginal cost of renewables is close to zero. However, since renewable generation plants are of a smaller scale, the cost of increasing fossil-fuelled capacity at a given point in time will be lower than the cost of increasing renewable capacity. To simplify, we embed marginal capacity costs into the renewable energy cost function such that marginal costs include not only operational costs but also the investment costs to increase capacity.

where H is the level of emissions from the rest of the economy for a emissions price equal to zero and h reflects how emissions from the rest of the economy react to changes in the carbon price.

The market clearing price is determined from equalling the demand for certificates from the power sector, e_1, and from the rest of the economy, $e(p_e)$, to the emissions cap, E:

$$e_1 + e(p_e) = E$$
$$e_1 + H - hp_e = E$$

Under this setting, the monopolist will maximise its profits subject to the policy incentives and constraints:

$$\text{Max } P(Q)(q_1 + q_2) - c_1(q_1) - c_2(q_2) + rq_2 - p_e e_1$$
$$\text{S.t. } e_1 + H - hp_e \leq E$$

where r is such that $q_2 \geq R$.

Rearranging,

$$\text{Max} P(Q)(q_1 + q_2) - c_1(q_1) - c_2(q_2) + rq_2 - p_e f(q_1)$$
$$\text{S.t.} f(q_1) + H - hp_e \leq E$$

4.3 Optimal Policy

The primary reason for the existence of environmental policies is the existence of a negative externality. In particular climate policies are designed to reduce GHG emissions that constitute a negative externality. Fossil-fuelled energy producers emit GHGs. If the cost of such emissions is not internalized, there will be an excessive production of the externality affecting negatively welfare. Conventional economic theory teaches us that a tax on the externality (or a subsidy on the "avoided" externality) can restore social efficiency.[14]

The introduction of a tax on emissions from fossil-fuelled electricity generation restores efficiency. Carbon markets and carbon taxes aim at internalizing the cost of

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[14] Under the presence of a negative externality from the production of a product, a tax on the externality or a subsidy for not producing the externality are equivalent. A subsidy to green energy can however affect negatively the price of fossil-fuelled energy and cause an inefficient increase in its consumption. Gelabert et al. [13] estimate that an increase of 1 GWh in the production of renewable energy implies a fall in the price of 2 € per MWh. Also, given the heterogeneity of energy sources, it is not trivial to design a subsidy that reflects avoided emissions (while in the case of a tax, the identification of the object of the tax is easier). See Borenstein [6] for a discussion on this issue.

the emissions externality and thus restoring efficiency.[15] Alternatively, a Pigouvian subsidy on avoided carbon emissions could have equivalent effects: by subsidising emission reductions (from a pre-specified benchmark), the global optimal might also be restored.[16] Both instruments, under certain circumstances, lead to the same outcome.

In principle, a carbon price through the setting of a system of tradable "black"[17] (CO_2) quotas such as the EU ETS or through carbon taxes should be sufficient to abate emissions and restore optimality. A carbon price provides a price signal to firms which is incorporated into their production and investment decisions and allows them to adopt the most efficient decision on how and by how much to reduce their carbon emissions.

In the absence of any policy, the electricity mix would be such that the marginal costs of the fossil-fuelled generation and the non-emitting sector are equal, i.e. $c_2'(q_2) - c_1'(q_1) = 0$.

In our simple model, the existence of a carbon market (and no renewable subsidies) would be equivalent to setting $r = 0$ (and $R = 0$). Producing one more unit of electricity through fossil-fuelled technologies would imply incurring the production costs and the emissions costs. This would increase the demand for carbon permits which would cause an increase in the emissions price. Therefore, the marginal cost of producing one more unit of electricity through fossil-fuelled technologies would be higher than in the absence of a carbon price. This would promote non-emitting generation.

Under this scenario, the electricity mix would be such that marginal costs of both technologies are equalised, i.e.$c_2'(q_2) - c_1'(q_1) - p_e f'(q_1) - p_e' f'(q_1) \leq 0$. Now, the marginal cost of the fossil-fuelled technology would be higher (since it would internalise the emission costs). A carbon market would therefore be sufficient to restore optimality.

Thus, a carbon market would suffice in principle to solve the emissions externality. Setting an optimal price for carbon would provide economic agents covered by the carbon market with a signal to reduce their emissions. Such a signal could trigger investments in renewable energies. The decision to invest in renewable energy will be driven by the relative cost of producing non-emitting energy versus the cost of producing fossil-fuelled energy once the emissions externality has been internalised. A carbon market does not necessarily entails the development of a renewables sector since economic agents might decide to reduce their emissions through clean investments in other sectors where the abatement costs might be lower.

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[15] For a discussion of the role and determination of the carbon price see Bowen [7]. In the US, there is no carbon price so the internalisation of GHG emission costs corresponds to renewables support mechanisms. See Joskow [18].

[16] Note however that such a subsidy would not justify different subsidies to different non-emitting technologies.

[17] Böhringer and Rosendahl [5].

The superiority of carbon pricing policies alone over any alternative policy mix is based on the additional cost that support mechanisms for renewable energy sources for electricity (RES-E) imply for the abatement of emissions, the lower effectiveness of RES-E to reduce carbon emissions and the negative impact RES-E deployment has on emission prices, which might delay investments in other more efficient options to reduce carbon emissions.[18] Therefore RES-E support mechanisms are at best, redundant and likely to generate excess cost.

5 The Case for Additional Instruments

What could justify the existence of additional instruments on top of carbon pricing policies? The economic literature finds basically two main groups of reasons for setting additional instruments to reduce carbon emissions[19]: First, if there are imperfections in the carbon market which lead to too low a carbon price; and second, to promote the positive externalities of non-appropriable investments in R&D that will contribute to reducing the carbon abatement cost.[20]

There are many other reasons why governments might decide to support renewables such as promoting renewables as industrial policy, job creation or energy independence. However, such reasons do not seem to respond to the existence of market failures or, at least, not to market failures exclusive to the renewables industry. Therefore, such justifications will not be addressed here.

5.1 Carbon Market Imperfections

The first argument would be related to the existence of market imperfections or design flaws which make that the carbon price alone is not effective to attain a specific target. Such lack of effectiveness could be caused for example by an allocation of excessive number of carbon credits that makes the CO_2 target non-binding (and thus, the carbon price close to zero) or by the possible inconsistencies between short-term carbon markets and long term climate objectives which might result in an inefficient carbon price path.

[18] See e.g. Del Río [20], Böhringer and Rosendahl [5], Abrell and Weigt [1].

[19] See Borenstein [6].

[20] Other common market failures discussed by the literature are asymmetric and imperfect information and principal-agent problems (which might explain household decisions to underinvest in renewable technologies but are not very much applicable to firms as explained by Gillingham and Sweeney [14]. Other justifications such as energy security, job creation, and driving down fossil fuel prices, are generally not supported by sound economic analysis.

As explained in Sect. 2, the EU ETS has presented several market imperfections that have depressed the price mostly due to the excessive number of permits in the market.

In our model, this would be equivalent to the cap E being set too high so that the emissions permit price would be close to zero. The cap E can be set too high for political reasons, i.e. governments might not want to impose a heavy burden on their domestic industries and therefore might opt for relaxing the emission caps, or for technical reasons, i.e. because of uncertainty about the right level of emissions or because of market imperfections.

Under this scenario, a second target such as a RES-E quota, might act as a safety policy to guarantee a minimum level of emissions reduction. In other words, a policy based on reducing emissions through a subsidy to renewables might increase the cost of abatement but, on the other hand, might be the only feasible option to reduce emissions.

In our model, imagine that the optimal level of emissions is E^* and because of political reasons or measurement errors is set at $E > E^*$ (or simply assume that because of market imperfections the carbon market will not be able to meet a cap of E^*). Should the fixing of the carbon market not be feasible, a subsidy to the deployment of renewables could be used as an alternative instrument to reduce emissions.

Using a RES-E quota to reach a specific emissions reduction, would require setting the renewables target R^* that will guarantee that the level of emissions will be E^*. That is, R^* is such that $f\left(q_1^*\right) + H - hp_e \leq E^* \leq E$ where q_1^* is such that solves

$$\text{Max } P(Q)(q_1 + q_2) - c_1(q_1) - c_2(q_2) + rq_2 - p_e f(q_1)$$
$$\text{S.t.} f(q_1) + H - hp_e \leq E^* \leq E$$

where r is such that $q_2 \geq R^*$. Solving the above equation, the necessary subsidy to produce R^* will be equal to the difference between the marginal cost of the renewable and the conventional technologies minus the emissions marginal cost of the fossil-fuelled technology, i.e., $r^* = c_2'(R^*) - c_1'\left(q_1^*\right) - p_e f'\left(q_1^*\right) - p_e' f\left(q_1^*\right)$.

Notice that a large R^* will increase the marginal cost of producing renewable energy and will simultaneously depress the emissions price. Therefore, the larger R^* the larger the necessary subsidy via these two effects.

The lower abatement cost associated to a lower emissions price will not however compensate the higher costs associated to the subsidisation of renewables: subsidising renewables beyond the optimal level will increase total abatement costs.

In summary, the support to RES-E to overpass the imperfections of carbon markets is a second best policy option. The first best policy to reduce emissions would be to fix the carbon market but this might not be politically feasible, might take time, might not be feasible due to the large degree of uncertainty about future emissions or might not be effective because of the incompleteness of the carbon market. In the meantime, a direct subsidy to the deployment of renewables might do the job though at a higher cost. Such subsidy should internalise the impact of the renewables quota on the carbon market.

5.2 Non-appropriable Technology Externalities

A second argument to justify the existence of renewable energy support mechanisms would be the existence of non-appropriable technological externalities. Positive externalities of innovation exist in several sectors and per se do not justify the existence of specific subsidies. Innovation externalities justify horizontal support to R&D, but not sector-targeted support. However, in the case of climate technologies, innovation can decrease abatement costs. Thus, supporting positive innovation externalities would help to reduce the cost of the emissions externality. Innovation in climate technologies is a tale of two market failures: synergies between the innovation externality and the environmental externality help to reduce the abatement costs (See [17]).

Innovation externalities can arise from the investment in R&D or from learning-by-doing. Learning by doing occurs when a technology becomes more efficient the more it is used. Investment in R&D can reduce the cost of non-emitting technologies or can reduce the emissions of fossil-fuel technologies through better carbon efficiency or through carbon sequestration. The appropriate policy is different in each case, and also the interaction between policies.

5.2.1 Learning by Doing

Learning by doing implies that the costs of producing renewables are reduced the more renewable energy is produced. To analyse the effect of learning by doing we need to add a second period to our model: During the first period the monopolist decides how much energy from renewables sources to produce. The more renewables it produces during the first period the less costly will be to produce renewables in the second period.

This would be equivalent to adding a second stage to our model where the renewables cost function is $g(q_2^1) * c_2(q_2^2)$ where $g(0) = 1$, $g(q) \leq 1$ and $g'(q) \leq 0$ and q_2^1 and q_2^2 are the renewable energy production in periods 1 and 2 respectively. That is, $g()$ would reflect the decrease in the costs of producing renewables due to the effect of learning by doing i.e. the more renewables are produced in period 1, the lower the cost of producing renewable energy in period 2.

In the case of a monopolist, learning-by-doing effects would provide more incentives to produce renewable energy during the first period that in the absence of such effects (even if there is no subsidy). Since all the benefits will be captured by the firm in the second stage, the firm will produce more renewable energy during the first period than in the absence of learning by doing (or, equivalently, the necessary subsidy to reach a specific target R will be lower) in order to reduce the costs in the second period.

Therefore, learning-by-doing effects do not justify the existence of a subsidy to renewables when firms will be able to capture the benefits from learning by doing effects during the second period. In such a case, firms will have incentives to produce more renewables during the first period without additional support. The ability to capture the benefits from learning by doing is not necessarily associated to monopoly power, but may also be associated to the existence of patents.

However, in the case where firms are not able to appropriate the results of their investment, public support is justified. If learning by doing effects constitute a public good (i.e. cost reductions arise from general industry experience and not only from individual industry experience) then, as in the case of other public goods, firms will produce suboptimal amounts during the first period. That can justify a renewables target during the first period and, consequently, a subsidy to promote the production of RES-E during the first period.

In summary, only in the presence of learning-by-doing based on industry experience and of sufficient competition in the production of electricity, a subsidy to renewables would be justified. Ideally, such a subsidy should be proportional to the learning-by-doing spillovers.

There is however little evidence of the existence of learning by doing in the renewable industry and, also, such effects are not easily quantifiable.[21] It is therefore complex to justify a RES-E support mechanism based on learning-by-doing effects (and also to assess whether the amount of such subsidy responds to the learning-by-doing spillovers).

5.2.2 R&D Investment in Renewables

Investment in R&D reduces the cost of producing renewables. In our model R&D investment can be modelled as an investment cost I which reduces the production costs by $1 - G(I)$, where $G(0) = 1$, $G(I) \leq 1$ and $G'(I) \leq 0$. The renewables cost function in the presence of R&D would be $G(I) * c_2(q_2) - I$. The profit function of the monopolist would therefore be:

$$\text{Max } P(Q)(q_1 + q_2) - c_1(q_1) - G(I)c_2(q_2) + rq_2 - p_e e_1 - I$$

R&D investment would increase the competitiveness of the renewable technology and would therefore reduce the subsidy necessary to meet a specific renewable target.

The existence of positive externalities from R&D investment could justify subsidies to R&D but not subsidies to the deployment of renewables. Again, subsidies to R&D make sense only if there are positive externalities from R&D and these cannot be captured by individual firms. If benefits from R&D are fully captured by the R&D investors, then there is no justification for subsidies.

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[21] As Borenstein [6] states, "most studies of learning-by-doing are not able to separate learning-by-doing from other changes" and "the evidence of strong learning-by-doing is thin and credible results on spillovers are even more rare".

5.2.3 Investment in Carbon Efficiency

Improvements in the carbon efficiency of fossil-fuelled technologies would affect the emissions function $e_1 = f(q_1)$. Improvements in the carbon efficiency reduce the emissions per unit of output of fossil-fuelled energy. This would translate into lower carbon prices and larger production of the fossil-fuelled energy.

Paradoxically, the improvement in carbon efficiency would increase the competitiveness of carbon emitting technologies and thus higher subsidies would be required to meet a specific renewables target R. However, better carbon efficiency of fossil-fuelled technologies reduces emissions and thus reduces the need for supporting renewables.

6 Conclusions and Policy Recommendations

We know that the use of fossil fuels generates GHG emissions and, thus, imposes external costs on present and future generations that are not reflected in its market price. This encourages the consumption of non-renewable energy above its socially optimal level. Pricing correctly the externality costs is therefore the most efficient policy to restore optimality. Consequently, GHG emission caps (and associated carbon prices) or carbon taxes are the best policy to reduce carbon emissions. However, additional policies may be justified when the carbon policies show imperfections and design flaws, or in the presence of other market failures.

This chapter focuses on the interaction between carbon markets and RES-E support mechanisms. A number of conclusions can be reached in such context:

First, if emissions are subject to a binding cap and the emissions market is well designed, then expanding the renewables production does not bring any additional benefits in emissions reductions. Yet, theoretical and empirical studies show that such policies tend to increase the cost of emissions reduction in comparison with a policy based on carbon prices.

Second, additional policies aiming to support the production of RES-E may be justified in the presence of imperfections or design flaws in carbon policies and in the presence of non-appropriable spillovers from technological innovation. Nevertheless, empirical evidence shows that the cost of reducing emissions is larger when the two policies are simultaneously activated. Therefore, the use of other policy instruments should be limited to the cases where their expected benefits are verifiable.

Third, RES-E support policies tend to reduce carbon prices and decrease wholesale electricity prices. However, retail prices will be higher if subsidies are recouped via uplifts on electricity retail prices. This, in turn, reduces the relative costs of fossil fuels versus renewable energy, which carries two major risks that should be addressed. One is the reduction of the final demand for electricity and the increase in the share of fossil fuels final consumption. The other risk is low-emissions fossil fuel, for instance gas, being replaced by high-emissions fossil fuels, such as coal, in the production of electricity. So, paradoxically, it may turn out that RES-E support programmes end up promoting the dirtiest technologies.

Fourth, subsidies or other support schemes to renewables aiming to correct carbon market flaws should be set according to marginal damages. R&D subsidies should reflect the spillover rate and RES-E production should be subsidised in proportion to the spillovers resulting from learning-by-doing. However, in practice this is not always feasible and the promotion of specific technologies is linked to the cost difference with the marginal competitive technology. This may bring inconsistencies that should be carefully addressed.

Fifth, the climate policy mix should be carefully designed to take into account potential interactions between policy instruments. RES-E support mechanisms should address the market failure they aim to solve, be it carbon market imperfections or non-appropriable technology externalities. The impact of RES-E support mechanisms on carbon prices should be included in their design to avoid unwanted effects. The danger that a bad design increases the cost of carbon reduction and fosters the use of dirtier technologies is real.

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When and How to Support Renewables?—Letting the Data Speak

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Abstract Low-carbon energy technologies are pivotal for decarbonising our economies up to 2050 and being able to at the same time ensure secure and affordable energy supplies. Consequently, innovation that reduces the cost of low-carbon energy sources would play an important role in reducing the cost of the transition. In this paper we want to assess the two most prominent innovation policy instruments (i) public research, development and demonstration (RD&D) subsidies and (ii) public deployment policies. Using a Lasso-regression we are able to select a model that is best able to perform in-sample predictions of patenting behaviour and international competitiveness in 28 OECD countries over 20 years. This approach allows including two dozen variables as well as a wide range of lags of the variables and interactions between them—in total some 47,000 variables. Our results indicate that both deployment and RD&D coincide with increasing knowledge generation and improving competitiveness of renewable energy technologies. According to our estimates, if Germany had invested one standard deviation more in deployment and RD&D support for wind technology than it actually did from 2000 on, the number of German wind patents would have been 166 % higher in 2009. If it only increased deployment the number of patents would have been 20 % higher and if it only increased RD&D the number of patents would have been 122 % higher. This indicates two things. First, both support schemes together have a higher effect than the two individually. And second, RD&D support is unsurprisingly more effective in driving patents. Thereby, timing matters. Current wind deployment based on past wind RD&D spending coincides best with wind patenting. If we look into competitiveness we find a similar picture. A hypothetical increase in German deployment and RD&D support for wind technology by one standard deviation from 2000 on

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would according to our estimates, coincide with an improvement from 8th to 7th position in terms of revealed comparative advantage of German wind turbines on the world market. Thereby, the largest effect comes from deployment. Finally, we find significant cross-border effects, especially for wind deployment. Increasing deployment in one country coincides with increasing patenting in near-by countries. Based on the above-presented findings we argue that both deployment and RD&D support are needed to create innovation in renewable energy technologies. However, we worry that current support is unbalanced. Public spending on deployment has been two orders of magnitude larger (in 2010 about 48 bn Euro in the five largest EU countries in 2010) than spending on RD&D support (about 315 mn Euro). Consequently, basing the policy mix more on empirical evidence could increase the efficiency of innovation policy targeted towards renewable energy technologies.

1 Introduction

All developed countries have been putting in place a number of policies to support renewable energy technologies for more than a decade and will continue to do so in the foreseeable future. The corresponding policies differ widely in scale, scope and design of legislation. However, none of the existing approaches is undisputedly accepted as effective and efficient. Hence, quantitatively benchmarking the different approaches is useful for structuring the discussion and identifying efficiency potential. To do this, we will first introduce the different rationales why to support renewables. We will than argue the most important policy to support them is to promote innovation in order to reduce the cost of a large scale deployment of yet uncompetitive technologies. Then, we will focus on the balance and timing of two main policy areas to drive innovation: deployment support and (public) research development and demonstration (RD&D) spending. We argue that numerous countries introduced deployment support and RD&D spending but that the allocation of funds between the two and timing resemble a 'shot in the dark'. Based on this motivation, we will analyse a 28 country panel to determine which menus of policies are most successful in driving innovation. Finally we will draw policy conclusions.

1.1 Why Support Renewables?

Renewable energy technologies have been publicly supported for several decades but the reasons for doing so changed over time. Public support to the development of biofuels and renewable energy generation were part of the war effort that aimed at ensuring and diversifying energy supplies[1] and providing technical solutions for

[1] E.g. half a million producer gas vehicles running on wood pellets were used in Germany during the war.

war-specific purposes[2] during the first and second world wars. The oil crises in the 1970s brought about substantive programmes for RD&D of photovoltaic cells and wind turbines in Europe and the US, as one tool to reduce dependence from Arab oil suppliers and shielding Western economies from high and volatile oil prices. The argument of renewables as a means to reduce import-dependency reappeared in the European public debate with the Ukrainian–Russian and Belarus-Russian ‘gas wars’ and the increasing oil and gas prices in the 2000s. With the Club of Rome report in 1972, the narrative on the finite nature of energy resources received high public attention. The argument became somewhat side-lined in the public debate in the phase of low resource prices in the 1980s but re-emerged with the ‘peak oil’ debate in the 2000s. It can be found as one rationale for public support for renewable energy technologies in numerous public documents. One side-benefit claimed for renewables is that, by replacing power production in fossil plants, they reduce pollution (NOx, SOx, VOCs, etc.) that has negative health and/or environmental externalities.[3] Since the 1970s, the awareness of anthropogenic climate change increased in the public debate. It culminated in the 1996 Kyoto Conference in which most developed countries committed to reduce greenhouse gas emissions. The International Panel of Climate Change (IPPC) reports reiterate that containing global temperature increase requires a reduction of emissions from fossil fuels while the baseline scenario expects increasing emissions. Consequently, massive public support for renewable energy technologies was rolled out to replace existing fossil plants by yet uncompetitive renewable units in the short term and/or to reduce the costs of renewable energy technologies units to make them competitive in the long term. By the late 1990s the outlined narratives indicated that a growing market for renewable energy technologies will emerge. To anticipate this development, economic policy makers suggested supporting domestic renewable energy technologies in order to gain a competitive edge in this growing field (i.e. industrial policy). Furthermore, demand side polices in order to mitigate the economic crises of the 2000s envisaged public investments in renewable energy technologies. Consequently, industrial and macro-economic policies became a further rationale for supporting renewables. Finally, the nuclear accidents of Chernobyl (1986) and Fukushima (2011) undermined the public acceptance of nuclear as a source of clean energy in some countries, making renewables the only acceptable source (Table 1).

So we conclude that several different rationales have been used to justify past and present support for renewable energy technologies.[4]

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[2] E.g. Ethanol production from potatoes for fuelling German rockets or wind power for decentralised electricity production.

[3] One example: http://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/ee_innovationen_energiezukunft_bf.pdf (BMU 2011, p. 13).

[4] Most of the outlined reasons can be phrased as market-failure and hence a sensible case for public intervention can be constructed. See for example [12], p. 83ff).

Table 1 Rationale for public renewable energy technology support

Event	Rationale for public renewable energy support (RES)
WWI 1914–1918 and WWII 1939–1945	Military use of renewable energy technologies
Oil crises 1972 and 1979	Reduction of energy dependence, shield economies from oil price shocks
Club of Rome report 1972	Prepare for the finite nature of energy resources
1996 Kyoto Conference	RES as a means to mitigate carbon emissions from energy production
Since around 2000	RES support as infant industry policy
2008 crisis	RES deployment as demand-side macroeconomic policy
1986 Chernobyl, 2011 Fukushima	RES as a means to replace nuclear reactors
Side benefit	RES to reduce pollution (NOx, SOx, VOCs, …) from fossil plants

1.2 How to Support Renewables?

Already in the past, renewable energy technologies such as hydropower and geothermal energy have been widely used where they were competitive with other energy sources. Close-to-competitive technologies such as small hydropower plants were introduced in the market by preferential regulatory schemes and by pricing the externalities of fossil sources, e.g. through taxes and environmental regulations. However, competitive and close-to-competitive sources are in most countries unable to replace conventional plants in the volumes necessary to fulfil the above-outlined purposes. Consequently, renewable energy technologies that are not (yet) competitive with conventional sources are required.

There are essentially three complementary strategies to replace fossil sources by renewable energy technologies that are currently not competitive. The *first* one is to substantially subsidise the current renewables until they are competitive. The *second* one is to make all undesired technologies uncompetitive either by taxation or regulation. And the *third* approach is to support innovation in renewable energy technologies in order to reduce their cost in the future.

Full-scale replacement of conventional sources by currently available renewable technologies (stimulated by subsidies and/or making conventional sources less competitive) would be prohibitively expensive.[5] Consequently, innovation is essential.

[5] Thereby, the cost not only refers to the cost of the renewable energy technologies, but those of the entire system. For example, to achieve 100 % of electricity generation from solar and wind technology substantial investments into storage, networks and demand response are necessary. To give one excessive example, a 10,000 MW solar installation in Germany (~ 10 % capacity factor) costing about 10–20 bn Euro together with a 10,000 MW compressed air storage costing about 10 bn Euro would be able to flexibly deliver electricity the same way as a 1,000 MW coal plant worth about 2 bn Euro. To illustrate the magnitude of this effect, an economy wide shift from the current system to the outlined solar+storage system would increase electricity generation cost from less than 1 % of GDP to about 10 %.

Literature has identified two interacting innovation policies: (i) encouraging ‘learning-by-doing’ through government supported deployment of yet uncompetitive technologies and (ii) public RD&D as well as public support to private RD&D.

1.2.1 Deployment Driven Innovation

In recent years, both environment and economic research started focusing on endogenous technical change in the energy sector using learning curves. Arrow [1] first introduced this theory showing that ‘learning-by-doing’ acted as a driver to reduce costs through different channels.[6] Costs of production are modelled as a function of the cumulated capacity. A learning rate can be derived which estimates the reduction of cost per doubling of capacity.

$$c = \alpha * Cap^{\varepsilon}$$

$$LR = 1 - 2^{-\varepsilon}$$

where:

c	Unit cost (€/KW or €/KWh)
Cap	Deployment (cumulative capacity or production, etc.)
ε	Learning elasticity
LR	Technology learning rate

Learning rates played a role for official policy documents as well as they are crucial part of a cost benefit analysis for renewable energy support [6]. Learning curves can provide a justification of subsidies exceeding the direct effect of climate change mitigation as they decrease the long-term costs of new technologies. That is, deployment subsidies can lead to innovations in this sector which are more important than the direct reduction of green house gas (GHG) emissions in terms of social welfare [16].

1.2.2 RD&D Driven Innovation

The main purpose of RD&D is to generate innovations. Hence, it is little surprising that RD&D spending leads to innovations that can be measured in terms of patents. For example, Gurmu and Pérez-Sebastián (2008) develop a ‘patent production

[6] James and Köhler [6] note that there have been, “early applications of learning curves, between 1930s and 1960s”.

function' based on R&D and lagged R&D. They find that the (semi)elasticity of patents ranges between 0.4 and 0.7 suggesting decreasing return to scales.[7] As the current year accounts for over 60 % of total R&D elasticity, they conclude that R&D impacts patenting at an early stage of the R&D sequence.

Public RD&D spending on particular technologies is also deemed to create innovations.[8] For example, [3] find that public RD&D expenditure stimulates innovation in renewable energy technologies.

1.2.3 A Combination of Deployment and RD&D is Driving Innovation

Based on earlier literature Wiesenthal et al. [17] present a two-factor learning curve model that disentangles two of the most important learning factors: learning by doing and learning by researching. The latter describes the relationship between the accumulated knowledge stock and production costs. For a given technology t and time period y, the curve can be described as follows:

$$C_{t,y} = aQ_{t,y}^{-\alpha} KS_{t,y}^{-\beta}$$

where:

C	Costs of unit production (€/W)
Q	Cumulative Production (W)
KS	Knowledge stock (here: approximated through R&D investments, €)
α	Elasticity of learning by doing
β	Elasticity of learning by researching
a	Normalisation parameter with respect to initial conditions

Soederholm and Sandqvist [13] use a two-variable model using deployment and R&D to estimate the effectiveness of different subsidy schemes. They show that learning rates depend crucially on the specification used. Quantifying effects remains difficult and the authors stress that simultaneity can lead to possible biases as for example reduced costs can lead to higher deployment.

Lindman and Söderholm (2012) review 35 studies on learning rates for wind power and warn that results are econometrically spurious in most empirical estimates. They argue that more attention should be paid on "learning and knowledge spillovers in the renewable energy field, as well as to the interaction between technology learning and R&D efforts".

Koseoglu et al. [8] discuss the allocation of subsidies to either R&D or market application. Their conclusion is that R&D is underused compared to market application subsidies. A possible reason could be that short term effects of deployment are more visible than R&D and therefore favoured by policy makers.

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[7] Similar to Hall et al. (1986) who analysed data set from the seventies with similar models.

[8] This is despite crowding-out effects of private RD&D spending. See for example [10].

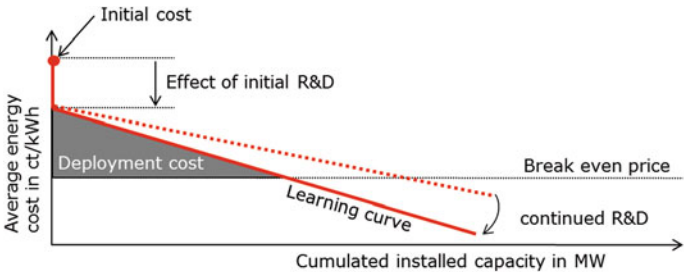

Fig. 1 Schematic picture of cost reduction for renewable energy technologies

However, too high deployment subsidies can induce lock-in into a (short-term) cost efficient technology preventing the development of other technology with higher long-term potential. Additionally, large subsidies can distort market incentives in a way that there is no net reduction in fossil energy use as the production of renewable energy units is very energy intensive. Public R&D on the other hand can fill the knowledge gaps covering areas which would not profitable for private R&D. In the US, states with transparent and openly available public R&D also attracted significantly more private R&D and venture capital in the respective sector [8].

The model can be extended with additional variables to account for other factors that drive technological change.[9] Johnstone et al. (2010) conduct a panel regression across 25 countries between 1978–2003 for renewable energy patents showing that with respect to patent activity taxes, obligations and tradable certificates are the only tools statically significant. The estimations exhibit that R&D spending is more effective for wind technologies whereas solar technologies are better supported by price incentives. Furthermore, stronger environmental legislation leads to more patents with heterogeneity across technologies: obligations and tradable certificates are most important for wind energy, which can be explained by the cheapest form of renewables hypothesis. According to their findings, solar energy on the other hand requires more direct investment support. Nonetheless, Johnstone et al. (2010) argue that in general most patent estimates are flawed due to country heterogeneity and time trends (Fig. 1).

Bettencourt et al. [2] explain the production of new energy patents in terms of new R&D investments and expanding markets based on a Cobb-Douglas production function. They find that 'most technologies show greater sensitivity to market growth than to public R&D investments though for wind the two contributions are similar'.

Summing up, literature provides some evidence of (i) decreasing returns to both, deployment and RD&D in driving innovation and (ii) a potential positive interaction of the two policy measures. In addition, the price of the competing technologies

[9] Popp [10] argues that the knowledge stock and the price of energy are important drivers of innovation in renewable energy technologies.

matters. This would indicate that innovation is best driven by a combination of RD&D and deployment. We summarise this interaction in Fig. 2. Innovations that cause system cost reduction are driven by (1) a certain amount of initial (or basic) RD&D that brings down the cost of the technology before the first unit is deployed, (2) learning-by-doing through the subsidised deployment of certain amount the technology, (3) a price on carbon making conventional forms of energy less competitive and (4) parallel RD&D expenses in order to speed up the learning. Finally (5), the break even for the new technology is contingent on how well the negative externalities of the incumbent technologies are priced in.

If this model were a fair description of reality, there should be an optimal combination of RD&D spending and deployment. In this case, one would expect that such an optimal combination is different for different technologies. The exact relationship is, however, impossible to determine *ex ante*. Nevertheless, *ex-post* analysis of existing support schemes should allow to learn on efficient timing and balance.

1.3 Renewables Support in Practice

Based on the rationales outlined in the first section (decarbonisation, import substitution, etc.), various support policies have been implemented with significant differences across countries and changes over time. Differences are partly explained by national differences in the prioritisation of the different aims. For example, if the

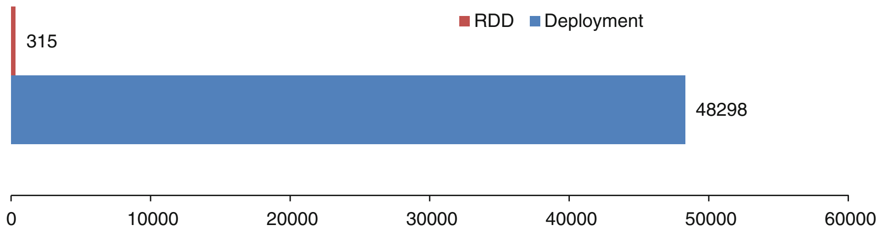

Fig. 2 Deployment versus RD&D expenditure for wind and solar in 2010 in six EU countries (in mn Euro). *Source* Bruegel calculation based on IEA and datastream. *Note* Net deployment costs are calculated as the difference of the deployment costs (Deployment costs are calculated as the installation costs per MWe multiplied with the deployed capacity. The country-specific costs per MWe are obtained from the “Projected Costs of Generating Electricity 2010” report of the IEA.) and the net present value of the future electricity generated (The net present value of future electricity generated is calculated by discounting future revenues which can be obtained by projecting the yearly energy prices (we use the price of a 2013 futures contract) and production of the respective technology in the respective country (differences across countries arise because of varying hours of sun/wind per year as well as different energy prices). We assume a nominal interest rate of 10 %). The countries are the five largest EU countries (DE, ES, FR, IT, UK) plus the Czech Republic (the largest Central East European country for which we have data)

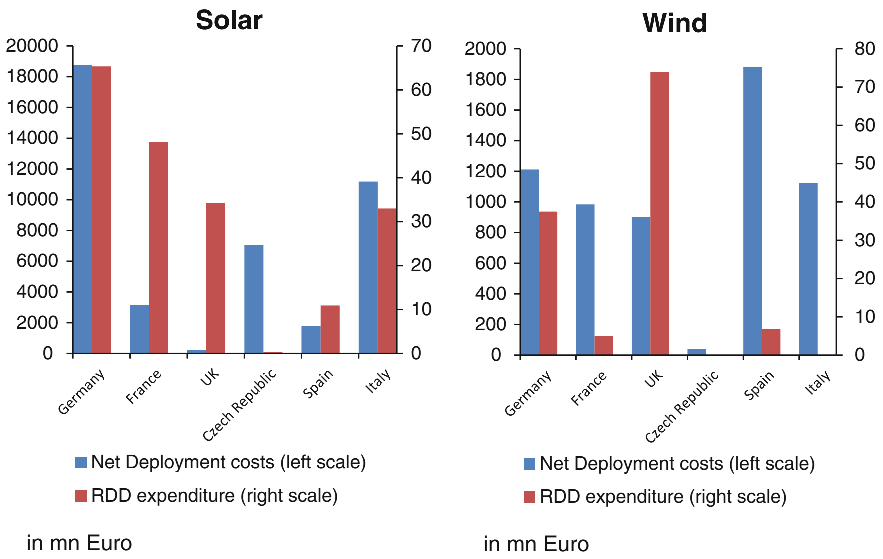

Fig. 3 Deployment versus RD&D expenditure for wind and solar in 2010 in six EU countries (in mn Euro). *Source* Bruegel calculation based on IEA and datastream. *Note* Net deployment costs are calculated as the difference of the deployment costs and the net present value of the future electricity generated

goal is decarbonisation, then emission pricing might play a more prominent role. If the concern is on industrial policy, instead, RD&D subsidies might be preferred. Finally, if security of supply is deemed to be more important, then deployment may be the focus. However, we cannot read the choice of a support mechanism or its intensity only as a techno-economic optimal response to the aforementioned challenges. In fact, every support mechanism produces substantial distributional effects, and institutional and information barriers are high. Consequently, without the complex political economy it is impossible to understand why different countries (and even regions) embarked on very different policy mixes.

There are different reasons why it is difficult to analytically identify optimal policy mixes: (i) the different rationales for renewables support, (ii) the numerous technology options, (iii) the substantial differences in the initial conditions, (iv) a wide continuum of combinations of support policies. According to Fig. 2, countries like Germany and Italy spent on RD&D less than 0.5 % of the budget for public support to the deployment of renewable energy technologies. Thereby, to our knowledge no country applies an 'analytic' approach for determining the policy mix that best suits the rationales. This resembles a 'shot in the dark' approach, and its persistence is astonishing, given the magnitude of the corresponding public spending (Fig. 3).

1.4 Research Question

Our research question is based on the above argumentation that (i) there are different rationales for supporting renewables; (ii) for all rationales, long-term cost reduction is key. Therefore, supporting innovation in renewable energy technologies is the major policy to achieve each of the policy goals; (iii) literature has identified deployment policies and RD&D spending policies as effective innovation policies; (iv) countries use a very heterogeneous set of balance and timing of the two policies.

The research question is whether innovation in certain renewable energy technologies (in our case wind and solar) can be best encouraged by a specific timing and balance of deployment policies and RD&D spending.[10]

2 Data

We build a panel of 28 OECD countries, covering the time period from 1990 to 2010. The main variables of interest—patent count, R&D expenditure and deployment—are provided by the OECD and IEA statistical services. We focus on the two most prominent renewable energy technologies: wind power and photovoltaic solar energy. These two sources accounted for about 64 % of newly installed capacities in 2012 in the EU, and accounted for roughly 7 % of total cumulative capacity by 2010. We follow the OECD classifications of patenting and spending into these two categories.[11]

Patents in this data set refer to granted patents and the dates referred to are the priority date, which is the date used by patent examiners to establish novelty. In effect this is the date of invention. This allows us to focus on the innovative timing without complications due to delays in different legal systems. However, since the dataset only includes granted patents, some data in later years is still spotty as, for example, a patent filed and assigned a priority date in 2010 might only be granted in subsequent years.

Similar to the literature on learning curves, we use lagged deployment and RD&D to explain technical change. The difference in our approach is that we proxy innovation by patents rather than costs. We consider the effects on patenting of (i) the knowledge stock, (ii) the deployment stock, (iii) technology spillovers, and (iv) country spillovers.

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[10] I.e., we will not evaluate individual instruments (such as 'green certificates' vs. 'feed in tariffs') or individual technologies (such as 'on-shore wind' vs. 'off-shore wind').

[11] http://www.oecd.org/env/consumption-innovation/44387191.pdf.

Table 2 Summary of main variables

	Units	Source	Coverage
Patent count	Absolute number	OECD	1990–2011
Installed capacity (deployment)	Megawatts	IEA, EIA[a]	1990–2011
RD&D expenditure	Millions of Euros (2011 prices and exchange rates)	IEA, OECD[a]	1990–2011 (missing in some years for some countries)

Notes Patents are measured with the OECD count system, where patents are fractionally allocated to countries according to the countries of the applicants
Deployment variables all refer to new deployment in a given year which is calculated from the change in total deployment, therefore data is available for one year less than the entire dataset
To deal with missing data we linearly interpolate the missing data values and we average the last/first 3 years in order to fill possible missing at the beginning or end
[a] For world total

The knowledge stock of each technology is measured as the cumulated sum of annual patents in the corresponding technology. The deployment stock is the cumulated sum of deployed technology, measured in MW. We use different discounting factors (0, 5, 10, 20 %) to account for the depreciation of the knowledge stock and the deployment stock over time. We account for technology spillovers by considering the impact of patenting and deployment in a given technology on the other technologies (i.e. patents and deployment in wind are included as control variables for the analysis in solar.) We also control for patenting and deployment in a broader range of renewables which includes solar thermal, geothermal, and wave energy. Country spillovers are taken into account by controlling for the deployment in the rest of the continent (e.g., one of the factors considered for explaining German patenting in wind energy is the deployment of wind power in Europe minus the German deployment). Furthermore, we also control for the deployment in all other countries weighted by the inverse distance. Here we use different distance measures, as provided by CEPII[12] (Table 2).

Table 3 provides descriptive summary statistics of the variables while Figs. 4, 5 and 6 plot the values of the key indicators for the EU and the US over the time period under consideration, 1990–2010.

The number of patents claiming a particular priority year (Fig. 4) demonstrates a sharp increase in patenting in wind and solar technologies after 2005. While the EU and the US claim about the same number of solar patents throughout the sample period, the EU patents significantly more in wind technologies than the US.

[12] Thierry and Soledad (2011) Notes on CEPII's distances measures: the GeoDist Database CEPII Working Paper 2011–2025—See more at: http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=6#sthash.ZE7LKOSm.dpuf.

Table 3 Descriptive statistics of main variables

	Min	Max	Mean	Std. deviation	Obs
Total patents	0	52433	3100	7447	616
pv patents	0	544	14	54	616
Wind patents	0	186	7	17	616
rdd renewables, M€	0	1807	51	119	498
rdd pv, M€	0	325	20	36	482
rdd wind, M€	0	152	7	12	469
Total deployment, MW	0	57050	1507	4232	609
pv deployment, MW	0	9303	109.3	658	609
Wind deployment, MW	0	9645	253.5	784	609

Observations per country, per year

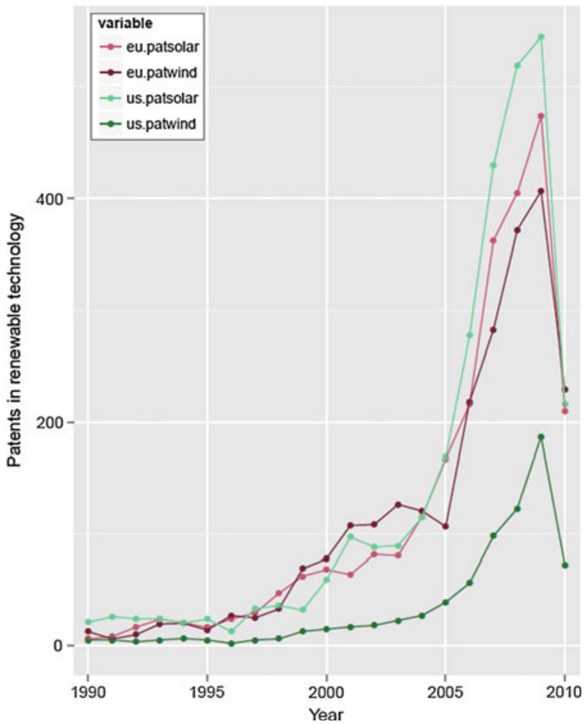
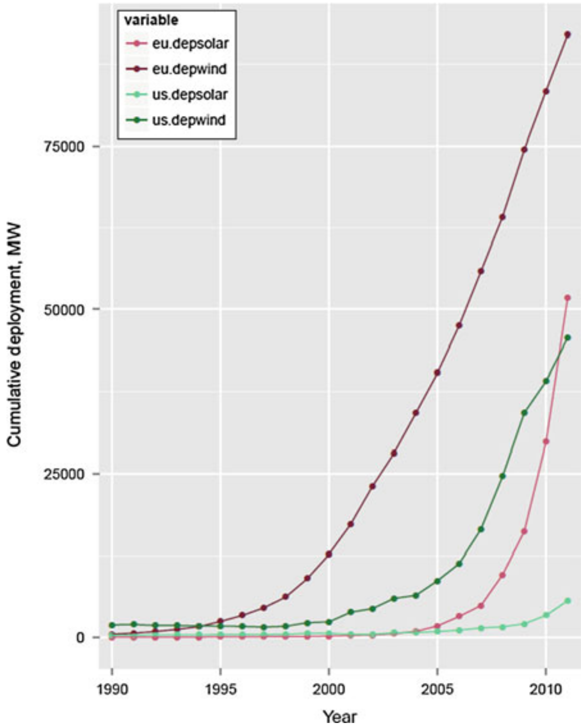


Fig. 4 Solar and wind patents US and EU

Despite the stronger patenting in solar, US solar deployment lags significantly behind US wind deployment (Fig. 5). On the other side of the Atlantic, EU solar deployment is outpacing EU wind deployment from 2009 on—cumulated capacities stay still larger.

Fig. 5 Solar and wind deployment in US and EU



When we consider RD&D (Fig. 6), we do see a small increasing trend after 2005 that slightly echoes the increase in patenting. Perhaps unsurprisingly, given the patenting figures, RD&D in solar is greater than in wind, lending support to a notion that connects RD&D spending with actual innovation.

Finally, as an alternative measure of the relative progress individual countries made in making solar panels and wind turbines produced in their county competitive on the global market, we use the revealed comparative advantage (RCA). In order to obtain an interpretable measure with a known distribution we use the ranking of the RCA-score for each country compared to our sample. To ensure the intuitive 'more is better', we invert the ranking, so that the worst country gets a 1 and the best country gets a score equal to the number of countries (28). To give an example, the US was a 'slightly above average' performer in exporting solar panels in the 1990s (inverse ranking score below 20), it became one of the most successful solar exporters in the early 2001–2002 (inverse ranking above 20) before it started to constantly lose competitive edge in solar exports until 2011 (inverse ranking 12) (Fig. 7).

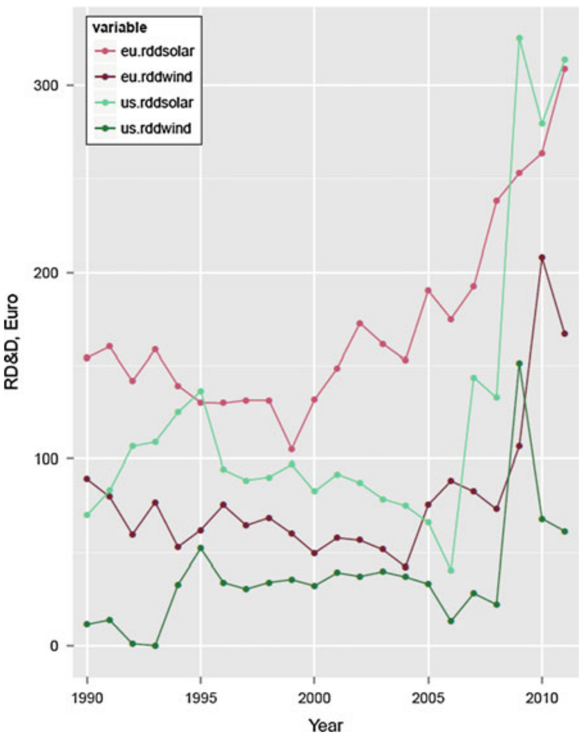


Fig. 6 Solar and wind RD&D in US and EU

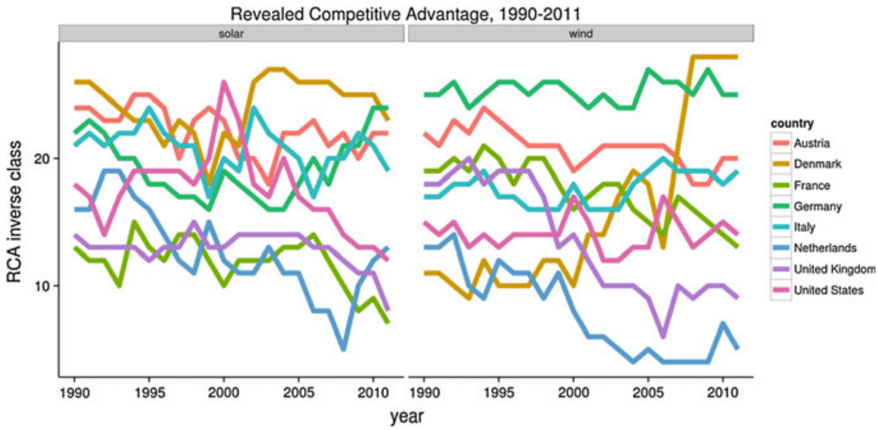


Fig. 7 Revealed comparative advantage position in wind and solar for selected countries, 1990–2011

3 Analysis

We do not possess a theoretical model that explains patenting in a certain technology in a certain country based on past deployment, RD&D spending and other variables.[13] While our prior belief is that both, deployment, RD&D spending and their interaction have all a positive effect on patenting, it is unclear to us how fast the corresponding inputs might generate innovation and whether this effect is linear or not. Consequently we decided to rely on a data-driven approach to select the relevant variables, time lags, operations (such as the logarithm) and interactions. To select the explanatory variables included in our model we proceed in five steps. First, we create four 'derivatives' of each of the original variables (level, log, square root and square). Then we include the first five lags in the set of explanatory variables. Third, we include all possible partial sums of consecutive lags, such as the deployment in the past 5 years, or the RD&D spending 3–6 years ago. Fourth, we include dummies for countries and years. Finally, we create all possible bilateral interaction terms between all these variables (original variables, derivatives, lags, partial sums and dummies). For example, one variable is the interaction of deployment in the last five years with the RD&D spending 3–6 years ago. This gives us more than 47,000 explanatory variables.

A standard panel regression of 28 countries times 20 years based on about 47,000 explanatory variables (that are suffering almost perfect collinearity) is obviously unfeasible. To select the explanatory variables that are most useful in explaining the patenting in certain technologies we employ a penalised regression approach (see [15],[14] the so-called 'Lasso'. Basically, instead of running an unconstrained optimisation problem (of SSR or likelihood), the Lasso does a constrained optimisation with a penalty. The Lasso is a particular case of shrinkage estimator. These are estimators that optimise on a restricted set of values for the coefficients of the variables. The penalty parameter can be chosen by the researcher, and controls how large this restricted set is. The particular form of the penalty function results in sets of different shapes. The Lasso penalty in particular results in subsets that have a corner at zero in all dimensions. The outcome is that the optimum is reached with many coefficients set exactly to 0. Hence, by its construction the Lasso performs a variable selection. Thereby, the larger the lambda, the more restrictive the variable selection is and the smaller the set of non-zero coefficients. In addition to the variable selection, the coefficients for all non-zero variables have been shrunk. While other selection mechanisms that do not apply shrinkage may be unstable because they are affected by collinearity, the Lasso overcomes this issue by construction.

[13] To our knowledge, existing models like "one factor learning curves", "two factor learning curves" or Cobb-Douglas patent production functions are not based on theoretical models either.

[14] As patents are typically discretely scaled (i.e., 1, 2, 3,…) we base the regression on a Poisson model.

This allows for two interpretable outputs: first, the order in which the different explanatory variables are included in the regression—when reducing lambda—is meaningful. It gives an indication on which variables contribute most to explaining the regressant.[15]

Second, the size and sign of the coefficients of a 'best' model can be interpreted. We define the best model as the model that best performs an n − 1 prediction exercise. That is, we do not focus on maximising the goodness-of-fit, but want to minimise the forecasting error. This allows an indication which combination of factors is best able to predict patenting and whether these factors have a positive or negative impact on the prediction. The standard Lasso does not come with an easy way to calculate the standard errors of the coefficient estimates, and a Bayesian approach would help in this regard. In any case, it is interesting to see which variables are most effective in explaining the variation in the explained variable, and in which direction this variation appears.

In order to make the results more easily interpretable, all variables are standardised. Also, model selection is restricted to models with at most 25 explanatory variables.

We present the result for solar in Table 4. The Lasso algorithm only selects 11 out of the 47,000 variables as being most relevant for predicting solar patenting behaviour.

The first, observation is that **rdd_solar** and **rdd_res**, i.e., the spending on RD&D for solar and the spending on RD&D for all renewables have a measurable effect. The delay with which **rdd_solar** increases patenting appears to be 3–4 years.

A second observation in that **pat_total** is important. We interpret this variable as a control for the overall patenting activity in a country/year.

The third important variable is market size. If **dep_total** is large, the impact of **rdd_solar** on patenting gets bigger.

The stability of the above-presented results is confirmed by a plot of the coefficients selected by the Lasso for a range of lambdas (Fig. 8).

For wind, a larger number of variables have been included in the estimation by the Lasso.

Again, total patenting (**pat_total**) is controlling for the general propensity to patent in a given country in a given year. And patenting in solar (**pat_solar**) seems even better suited to control for the propensity to patent in (renewable?) energy technologies.

Also, RD&D spending on wind technology seems to encourage patenting in this area. We find rather long and disperse time-lags for the effect of RD&D on

[15] For shrinkage estimators such as ridge or lasso 'f(betas) < c' for some function f and some constant c. With the ridge, f is the sum of the squares of the coefficients. Hence in the Ridge, all coefficients are non-zero, but a larger value is assigned to the coefficient that helps reducing the SSR the most. With the Lasso, f is the sum of the absolute values of the coefficients. Thus again, we obtain larger beta for variables that help reducing SSR, but in addition, the least significant coefficients are forced to 0.

Table 4 Results for solar photovoltaic

(Intercept)	2.849
pat_total_rooted	**0.183**
pat_total_rooted_lag2	0.071
pat_total_rooted_partsum1_lag1	0.003
pat_total_rooted_partsum2_lag1	0.022
rdd_solar_squared: dep_total_partsum3_lag3	0.050
dep_tech_lag3: rdd_res_squared_lag5	0.022
rdd_res_squared_lag5: **dep_solar**_partsum1_lag2	0.007
rdd_res_squared_lag5: **dep_solar**_partsum2_lag2	0.036
rdd_res_rooted_lag5: **rdd_solar**_rooted_lag4	**0.336**
rdd_res_rooted_lag5: **rdd_solar**_rooted_partsum1_lag3	0.000

Note Model chosen from >47,000 variables based on the lowest mean square error in predicting the n'th observation based on n − 1 data. Coefficients rounded at the third decimal digit. Number of included variables limited to 25 during model selection

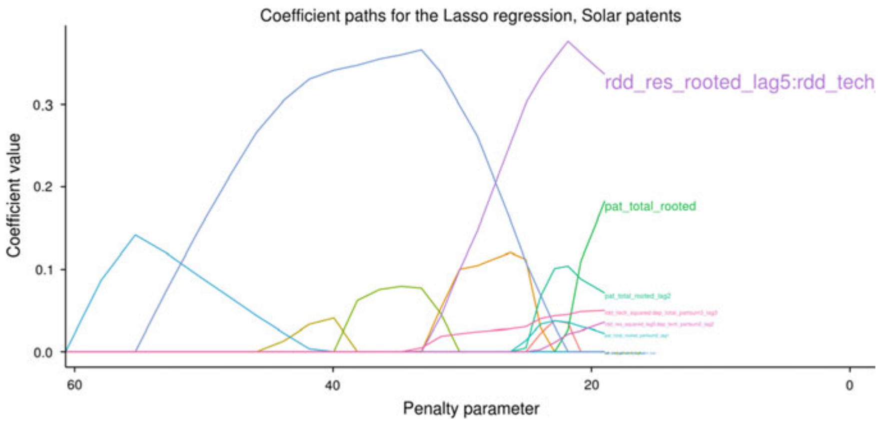


Fig. 8 Coefficients for solar patents at different lambda

patenting. RD&D between the second to sixth year (partsum5_lag2) seems to be most effective.

The most interesting finding in our view is that the effect of RD&D spending on wind technologies gets substantially augmented when the deployment of wind turbines on the continent is high (continent_**dep_wind: rdd_wind**). Again timing matters, current deployment based on past RD&D spending coincides best with patenting.

Table 5 Results for wind power

Intercept	2.014
continent_**dep_wind**_lag5: rdd_res_squared_partsum3_lag2	−0.055
continent_**dep_wind**_partsum4_lag3: rdd_res_squared_partsum1_lag3	−0.012
continent_**dep_wind**_partsum4_lag3: rdd_res_squared_partsum2_lag2	−0.068
continent_**dep_wind**_partsum4_lag3: rdd_res_squared_partsum2_lag3	−0.062
continent_**dep_wind**_partsum5_lag2: rdd_res_squared_partsum2_lag2	0
continent_**dep_wind**: **rdd_wind**_partsum5_lag3	0.009
continent_**dep_wind**: **rdd_wind**_rooted	0.062
continent_**dep_wind**: **rdd_wind**_rooted_lag2	**0.188**
continent_**dep_wind**: **rdd_wind**_rooted_partsum1_lag1	0.012
continent_**dep_wind**: **rdd_wind**_rooted_partsum5_lag3	**0.199**
dep_total_lag5: continent_**dep_wind**_partsum2_lag1	−0.003
dep_total: **rdd_wind**_partsum2	−0.008
dep_wind_dwdist: **rdd_wind**_dwdist	−0.016
dep_wind: **dep_wind**_dwdistwces	0.069
pat_solar_rooted_lag1	**0.36**
pat_solar_rooted_partsum1	0.034
pat_total_logged	0.068
rdd_res_squared_lag4: continent_**dep_wind**_partsum4_lag3	−0.045
rdd_wind_rooted_lag5	0.015
rdd_wind_rooted_partsum3_lag2	0.002
rdd_wind_rooted_partsum5_lag2	**0.346**

Note Model chosen from >47,000 variables based on the lowest mean square error in predicting the n'th observation based on n − 1 data. Coefficients rounded at the third decimal digit

Beyond these three main drivers, there are a number of variables with typically small negative values that are somewhat difficult to interpret. We would see them as correction factors that reduce the aforementioned effects in certain conditions. The largest is the interaction of RD&D spending on renewables with the deployment of wind on the continent (continent_**dep_wind**: **rdd_res**). One way of interpreting this is that countries with a lot of non-wind RD&D spending do not benefit (in terms of wind patents) as much from the deployment of wind turbines on their continent, as countries that focus their renewables RD&D on wind (Table 5).

The stability of the above-presented results is confirmed by a plot of the coefficients selected by the Lasso for a range of lambdas (Fig. 9).

To get some indication of the quality of our results we calculate the share of variance in the patenting behaviour our model is able to explain (similar to the R^2). The results are displayed in the following table. Given their parsimonious parameterisation the 'goodness-of-fit' performance of both models is impressive (Table 6).

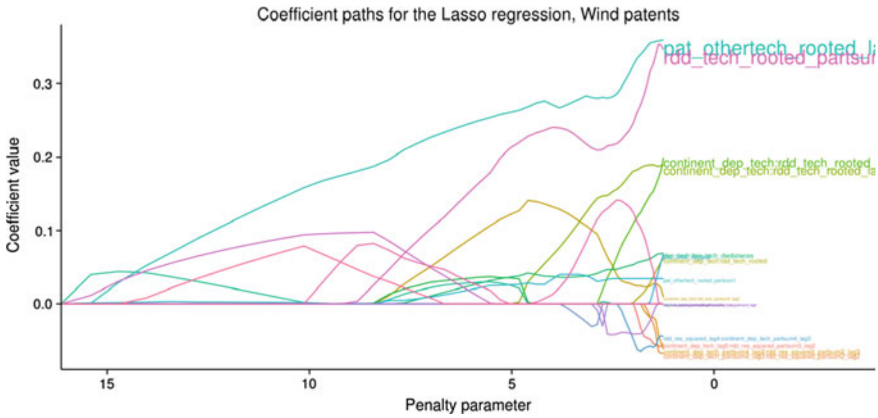


Fig. 9 Coefficients for wind patents at different lambda

Table 6 Deviance ratio for models explaining patenting behaviour in wind and solar

	Deviance ratio	No. of variables incl. intercept
Solar patents	0.73	11
Wind patents	0.75	22

Table 7 Magnitudes of the hypothetical shocks for Germany

	Deployment	RD&D
Solar	2,366 MW	17 mn Euro
Wind	950 MW	9 mn Euro

To display the size and timing of the effects suggested by our model parameterisations, we explore the consequences of a series of hypothetical shocks to our explanatory variables of interest. We focus on Germany in 2002, considering what path patenting would have taken in the years 2002–2009 if the country had increased deployment and RD&D individually by one standard deviation. We also consider the effects of a joint increase. The actual magnitudes of these hypothetical shocks are presented in Table 7.

3.1 Effect of Only RD&D Support

Increasing RD&D support by one standard deviation over a period of time has a substantial impact on patenting in this technology. Figure 10 demonstrates the effect for RD&D. An increase in solar RDD by 17 mn Euro per year from 2002 on would

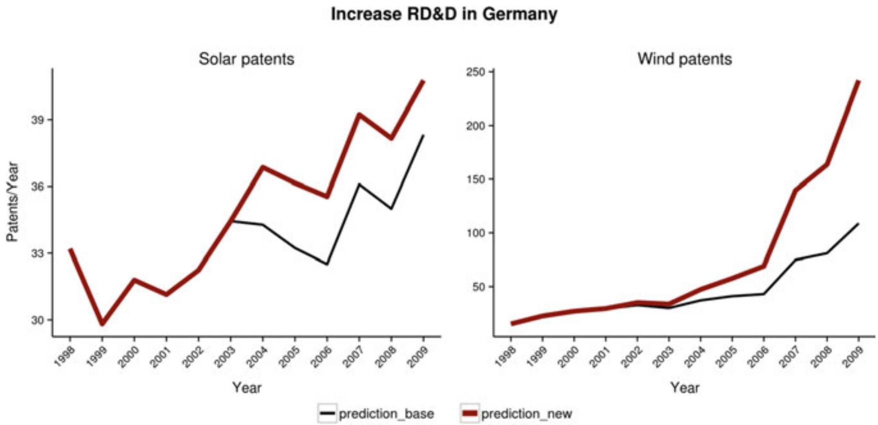


Fig. 10 Predicted response to an increase in RD&D spending in Germany by one standard deviation on patenting in solar (*left*) and wind (*right*) in Germany

according to the model we estimated coincide with increasing the number of patents by approximately 3 patents (9 % over baseline) per year in the subsequent period. This effect is even more pronounced when we consider wind patents, where the hypothetical scenario shows sustained increases in patents per year, going up to 100 % increases over the baseline.

3.2 Effect of Only Deployment

As presented in Fig. 11, the effect is rather different in the case of deployment. Here, an increase in solar deployment spending from 2002 onwards would according to our model coincide with increasing the number of solar patents by about 10 patents per year (approximately 30 % above the baseline). However, the effect is more muted for wind patents where we do observe an increase albeit a smaller percentage above the baseline.

3.3 Effect of Policy Combination

For the policy combination, we consider what could have happened if RD&D and deployment were increased simultaneously in the respective technologies. The results presented in Figs. 12 and 13 demonstrate additional patents that would result from the policy combination over the effects of either individual policy on its own. Here, the non-zero effects show us that the combination of policies is greater than simply the sum of their parts. In fact, for wind the additional benefit in terms of patents when joining policies is up to 25 % (1 % for solar).

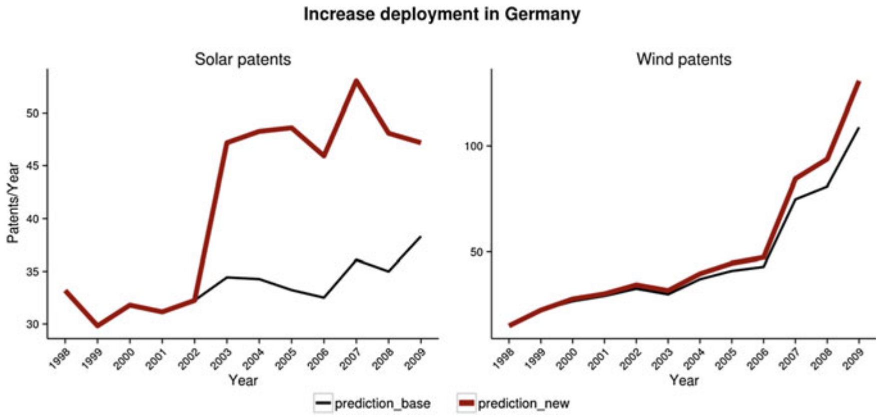


Fig. 11 Predicted response to an increase in deployment in Germany by one standard deviation on patenting in solar (*left*) and wind (*right*) in Germany

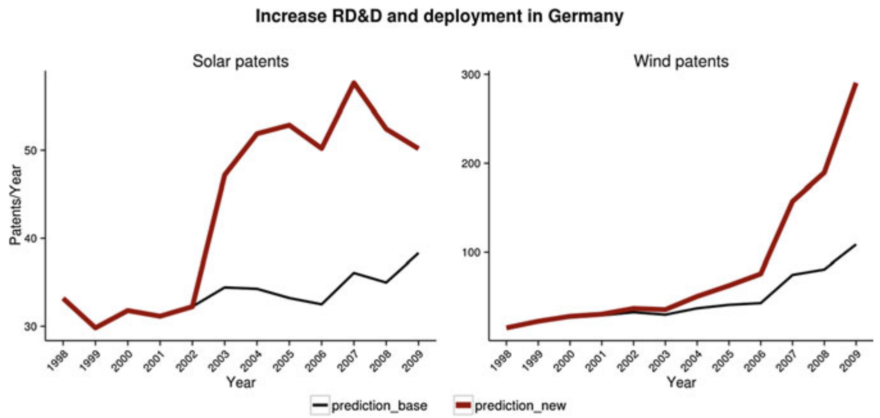


Fig. 12 Predicted response to an increase in RD&D spending and deployment in Germany by one standard deviation on patenting in solar (*left*) and wind (*right*) in Germany

3.4 Cross-Border Spill-Over

We also look at cross-border effects to analyse what impact either of the policies might have on patenting in neighbouring countries. Figure 14 present the results for Germany and its neighbours. We find the strongest effect for wind deployment which is shown to be associated with an increase in patenting of up to 20 % in some years for Denmark and the Netherlands.

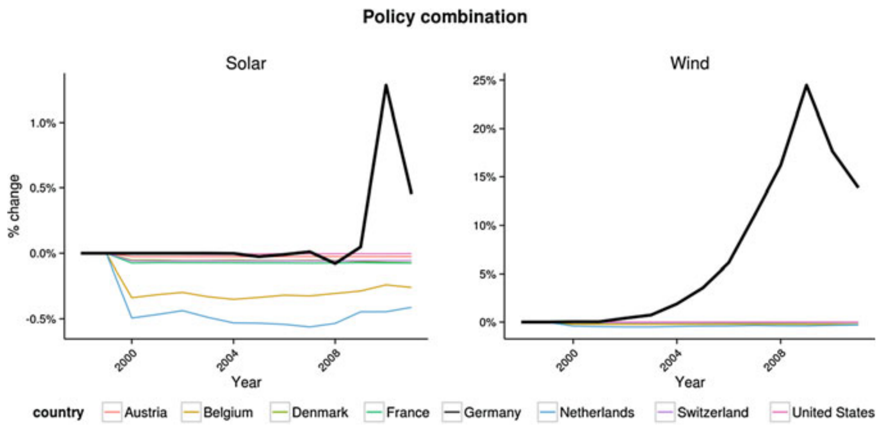


Fig. 13 Predicted difference between a combined increase in deployment and RD&D on patenting in solar (*left*) and wind (*right*) in Germany compared to the sum of the individual effects

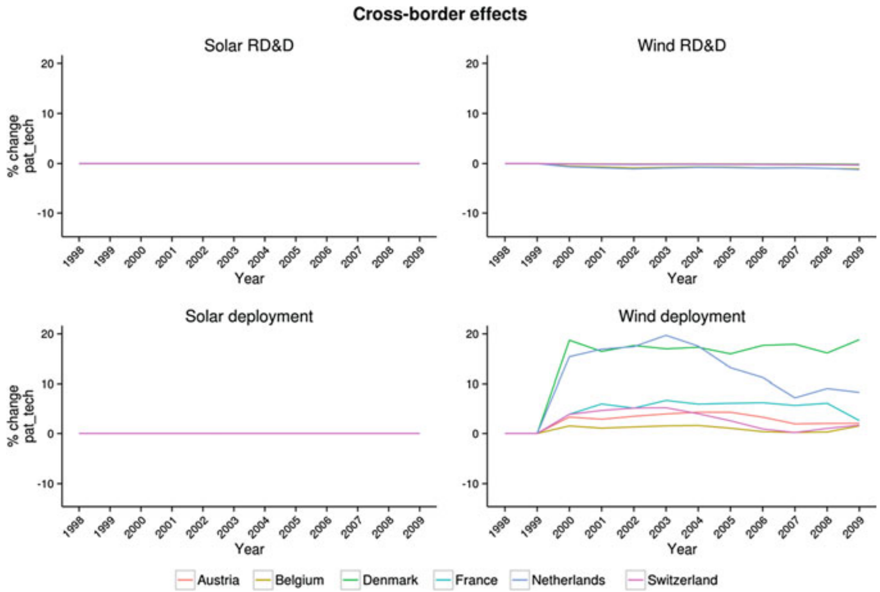


Fig. 14 Predicted response to an increase in RD&D (*above*) and deployment (below) by one standard deviation on patenting in solar (*left)* and wind (*right*) in Germany

Table 8 Deviance ratio for models explaining the RCA in wind and solar

(Sparse model)	Deviance ratio	No. of variables incl. intercept
Solar RCA ranking	0.29	23
Wind RCA ranking	0.46	23

3.5 From Patents to Competitiveness

The explained variable, number of patents in the narrowly define technology, is only an imperfect proxy for what policy would really care about—innovation leading to sustainable reduction in the total cost of using the technology to replace existing technologies.[16] To also capture cost-savings that improve the technology beyond patented innovation we repeat the analysis using the inverse RCA ranking. This should allow us to understand which policies (deployment, RD&D support or both) coincide with improvements in the competitiveness of the domestic renewable energy technology industry (Table 8).

Overall, the results for RCA are significantly less robust. Obviously, the comparative advantage and its development over time is determined by many factors do not properly control for (labour cost, education, capital cost, etc.). Consequently, the variation of RCA explained by a relatively sparse model of less than 25 variables is low if compared to the results obtained in the patents regression. Thus, the results below should be interpreted with a substantial degree of caution.[17] The major factor that helps predicting the revealed comparative advantage in wind and solar in a country, is the logged number of all patents granted in this country in this year (pat_total_logged, see Tables 9 and 10 in the Appendix). This indicates that a key driver of export specialisation in renewables is the innovative power of a country.

3.6 Deployment and Competitiveness

The clearest result for competitiveness is that deployment is indeed increasing the competitiveness of the corresponding technology. A sustained increase in domestic deployment of wind turbines increases the RCA ranking in wind turbines by about one position in the case of Germany. For solar panels there is also a clearly positive impact. Countries which deploy more solar panels are also exporting more of them in future. The clarity of the results somewhat surprised us, as our prior was that larger deployment coincides with larger domestic demand and hence more limited room for exports (Fig. 15).

16 Popp [11] for example argue that the diffusion of renewables is mainly driven by regulation and less by the knowledge stock.

17 We force the model selection to the subset of models that include 25 explanatory variables or less, as we noticed a tendency towards models with more than one hundred explanatory variables when only optimizing on the in-sample predictive power.

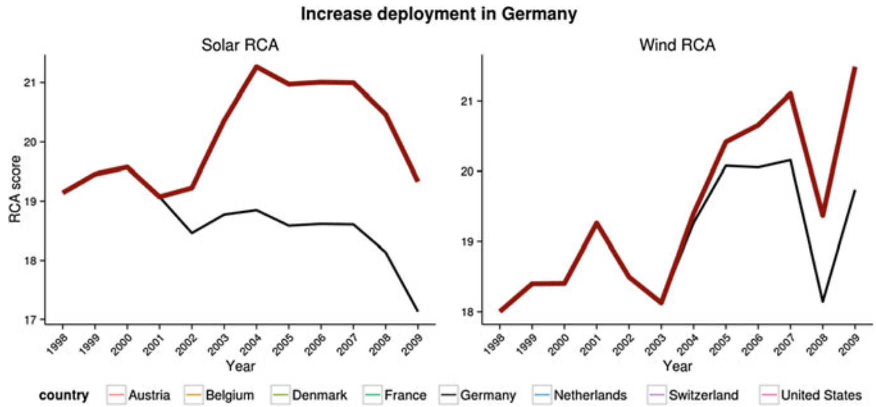


Fig. 15 Predicted response to an increase in deployment by one standard deviation on the RCA in solar (*left*) and wind (*right*) in Germany

3.7 RD&D and Competitiveness

The results for the impact of RD&D on competitiveness seem all not very meaningful. Our prior would be to find a positive impact of domestic support on RD&D support on the competitive position of the corresponding technology. By contrast, our results indicate that the impact of RD&D is insignificant (Fig. 16).

3.8 Policy Combination and Competitiveness

Similarly, the policy combination does not seem to lead to very meaningful results on competitiveness. The joint policies would increase the RCA score in wind

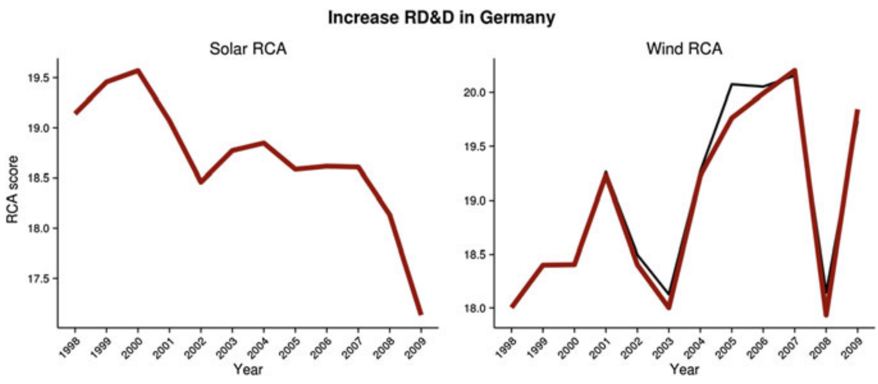


Fig. 16 Predicted response to an increase in RD&D expenditure by one standard deviation on the RCA in solar (*left*) and wind (*right*) in Germany

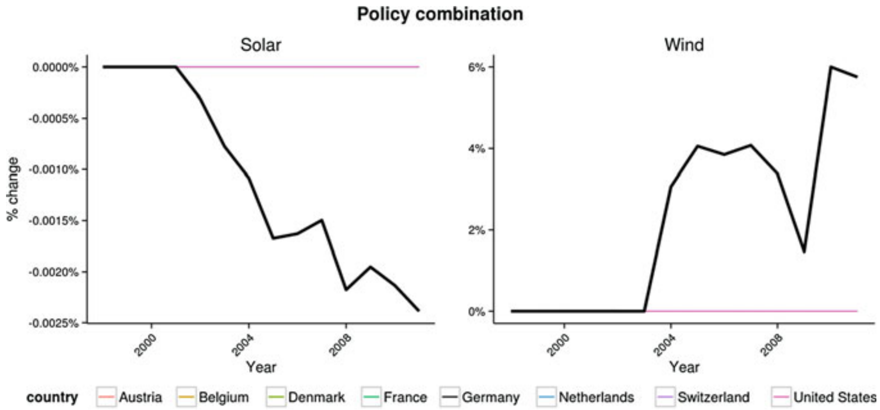


Fig. 17 Predicted difference between a combined increase in deployment and RD&D on the RCA in solar (*left*) and wind (*right*) in Germany compared to the sum of the individual effects

turbines above the baseline by about 4 % on average per year. In the case of solar panels, the joint policies would lead to a very small (less than 0.0025 %) decrease in RCA score; however, as in the case of RD&D alone, it is unclear whether this difference is significant. These results could loosely be restated as an increase in relative exports of wind turbines and a tiny decrease in relative exports of solar panels. However as outlined above, we would expect these policies to play only a small role in explaining overall changes in export competitiveness. What they do demonstrate clearly, and suggest as an avenue for further research, is a strong difference in how deployment and RD&D affect competitiveness in the given renewables fields (positively and significantly in the one case, ambiguously and close to insignificantly in the other) and the need to disentangle the joint effects for clear policy prescriptions on the choice of domestic renewables support and export competitiveness (Fig. 17).

4 Discussion

Our results suffer from a number of potential drawbacks:

- Additional explanatory variables and controls for locational factors (sun, wind conditions), neighbouring country effects, interaction terms, non-linear relationships and others could make sense.
- Our econometric approach does not allow us to fully explore the potentially complex interactions between the analysed variables. Whether a certain factor such as 'deployment in the past 5 years' is a true cause, or just an intermediate variable itself being caused by past knowledge stock and RD&D activities cannot be properly disentangled. In the same vein we cannot separate cause-and-effect

for explained and explanatory variables. Such endogeneity might for example arise because countries that were successful in renewable innovation in the past might feel encouraged to invest more in this field. Hence, our results do not allow us to properly assess the impact of additional RD&D spending in *t* on patenting in all subsequent periods, as this would require a (theoretically founded) structural model of all interactions.

- Furthermore, our model might just be an ‘explanation in hindsight’, meaning that it might explain those 13 years for the 28 countries but not earlier years or future years or other countries.
- The explained variable, number of patents in the narrowly defined technology, is only an imperfect proxy for what policy would really care about—innovation leading to sustainable reduction in the total cost of using the technology to replace existing technologies.[18] That is, we neither cover how patenting in complementary technologies such as storage is affected, nor can we measure unpatented innovation (such as process innovation or scale effects) that might have substantial cost-saving effects. We also do not know the actual cost-reduction effect of the patents. On the other hand, the relative competitiveness of exports on the global market—as measured by the RCA ranking—seems not to be a good proxy either.
- Furthermore, we cannot give meaningful p-values, so some of the coefficients might have just been included by chance. Going for a Bayesian approach might allow an assessment of the confidence we put into the individual parameter estimates. In addition, it would allow us to include prior information (such as interactions deduced from theory). Hence, a corresponding implementation is very promising but had to be left to further research.

Our results can at most shed light on what timing and balance of national support policies coincided with a certain patenting behaviour. This finding cannot, however, be directly translated into which policy combination is efficient. Such a ‘policy optimisation’ would require the parameterisation of the ‘patent production function’ to be complemented by a cost-function of the policies. Based on this, an ‘optimal’ policy balance and timing could be determined. Obviously, the parameterisation of the model would need to be constantly updated because the persistence of the interaction is not given. In fact, it would be akin to optimising a portfolio of policies in order to produce the maximum number of patents or maximise the competitiveness ranking. Similarly to financial hedging strategies, such a ‘portfolio optimisation’ approach would not work in the case of an event that was not observed in the historical data used for parameterisation (‘black swan’). Consequently, the choice of deployment and RD&D support policy should not be mechanically based on a quantitative optimisation strategy. Nevertheless quantitative ‘policy optimisation’ could serve as valuable additional tool in particular as a benchmark against existing (‘shot-in-the-dark’) strategies.

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[18] Popp [11] for example argue that the diffusion of renewables is mainly driven by regulation and less by the knowledge stock.

5 Conclusion

Our results are in line with the hypothesis that deployment and RD&D expenditure both have an impact on technology development. Our finding that the combination of deployment and RD&D expenditures has a positive impact on patenting is in line with two-factor learning curves.

Our results indicate substantial differences in the ‘patent production function’ between the two analysed technologies. While solar patenting strongly coincides with both past RD&D expenditures and deployment, wind patenting did not coincide with deployment alone, but was strongest in countries that featured a policy combination of RD&D expenditures and deployment. Whether this points to idiosyncratic learning curves for each technology, or whether certain technology families enjoy more similar learning curves or if technologies at a similar stage of maturity enjoy similar learning curves, is left for further research.

In addition, our results indicate that timing, cross-border spillovers and technology spillovers matter for the success of support policies. With respect to timing, the data suggests that a certain sequence of RD&D support and deployment is most strongly linked to patenting. In particular we find that deployment based on earlier RD&D expenditures strongly coincides with wind innovation. Cross-border spillovers play a positive role for wind deployment. Finally, we have (slight) evidence that technology spillovers might matter for patenting.

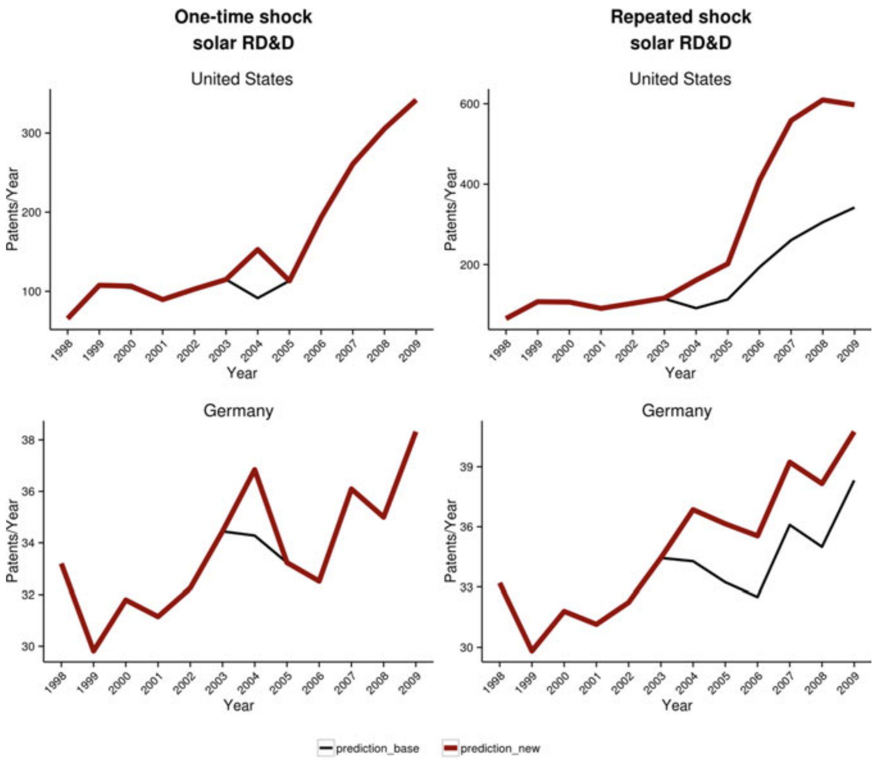
6 Policy Implications

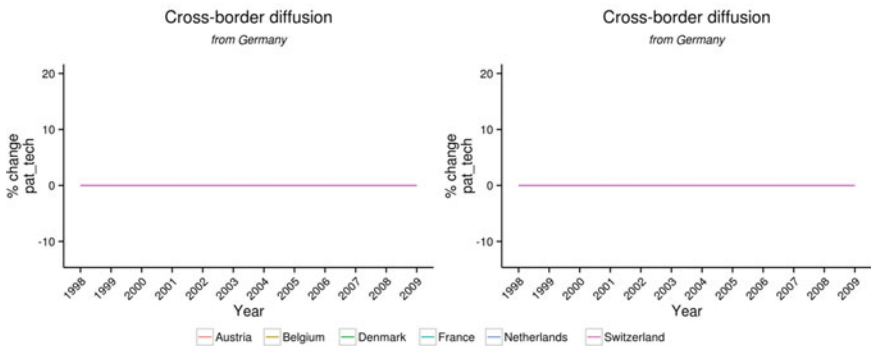
Our findings are in line with the hypothesis that both deployment and RD&D support are effective in advancing technology development. Our results also imply that the weight and timing of deployment and RD&D support matter. That is, certain combinations of deployment and RD&D support are more efficient than others. This calls for a strategic approach towards renewable energy technology support. Furthermore, the existence of substantial cross-border spillovers from deployment implies that international coordination might make renewable energy technology support more efficient.

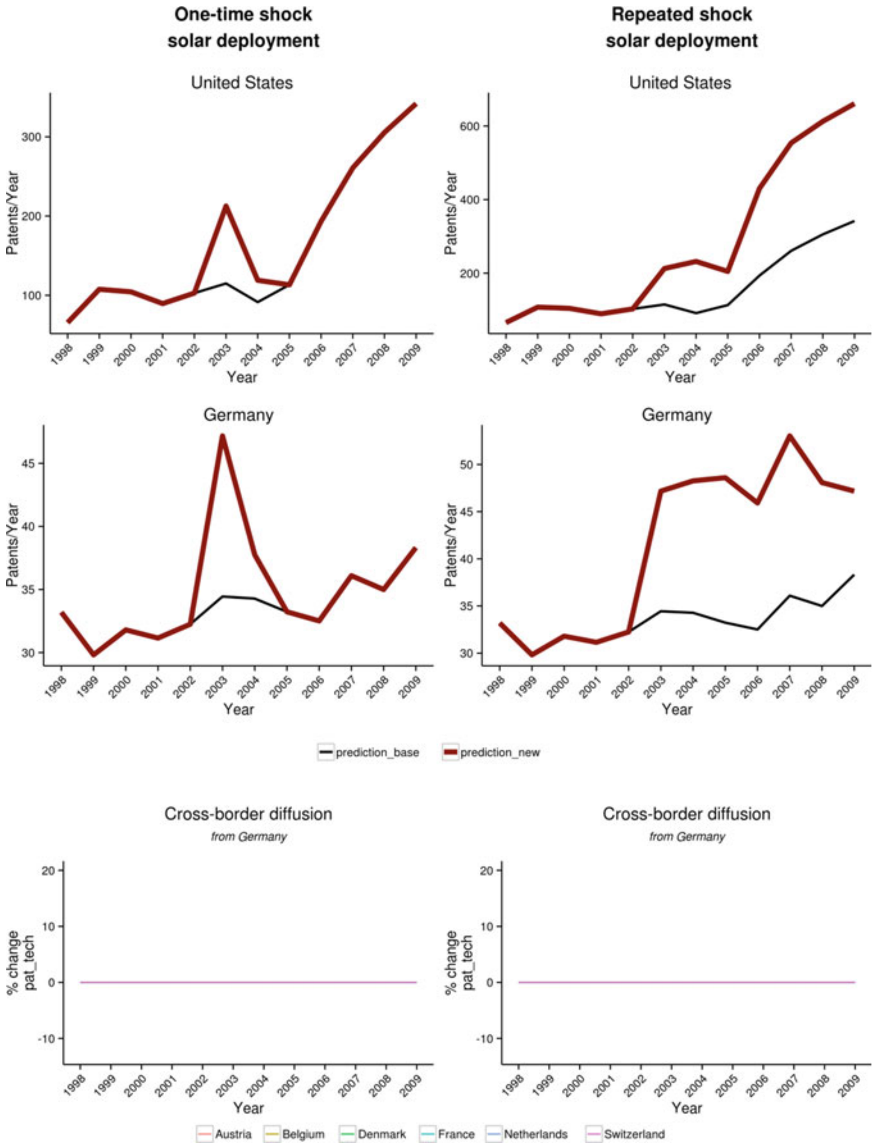
Consequently, going beyond an uncoordinated ‘shot-in-the-dark’ is worthwhile, though more research is necessary to identify support structures that are resilient and efficient. In this respect, given the size of the issue (recall: about 48 bn Euro spent on deployment and 315 mn Euro spent on RD&D support in the five largest EU countries in 2012) investing more in *ex-ante* and *ex-post* evaluation of renewable energy technology support schemes is a ‘no regret option’.

Appendix

A.1 Patent Regression






One-time shock
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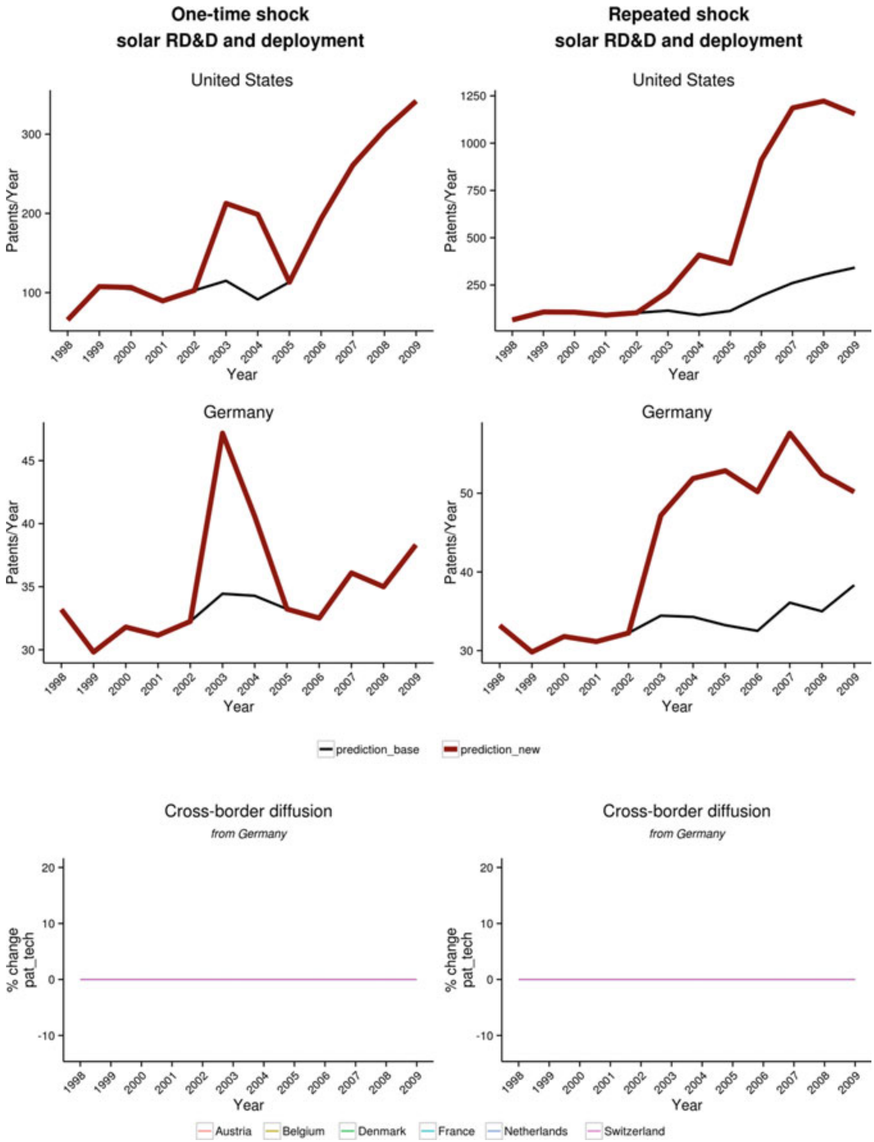
One-time shock
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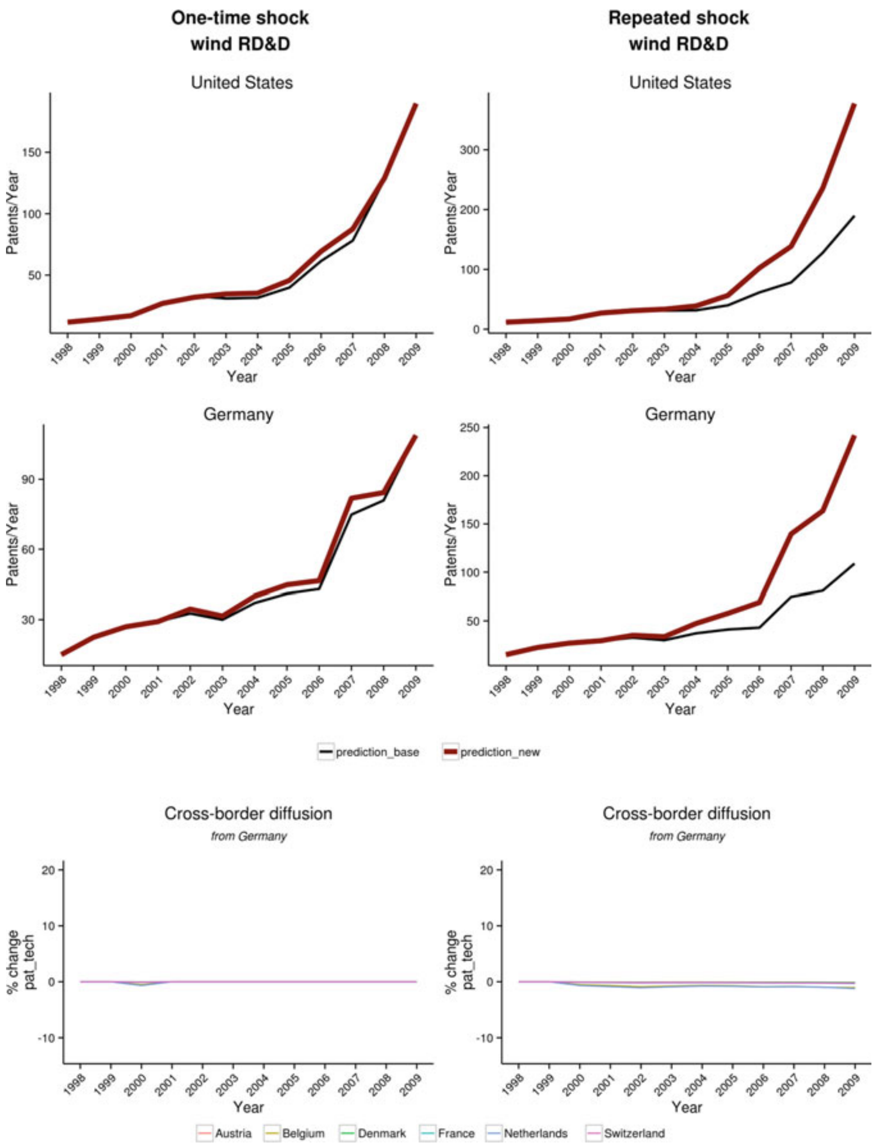
One-time shock
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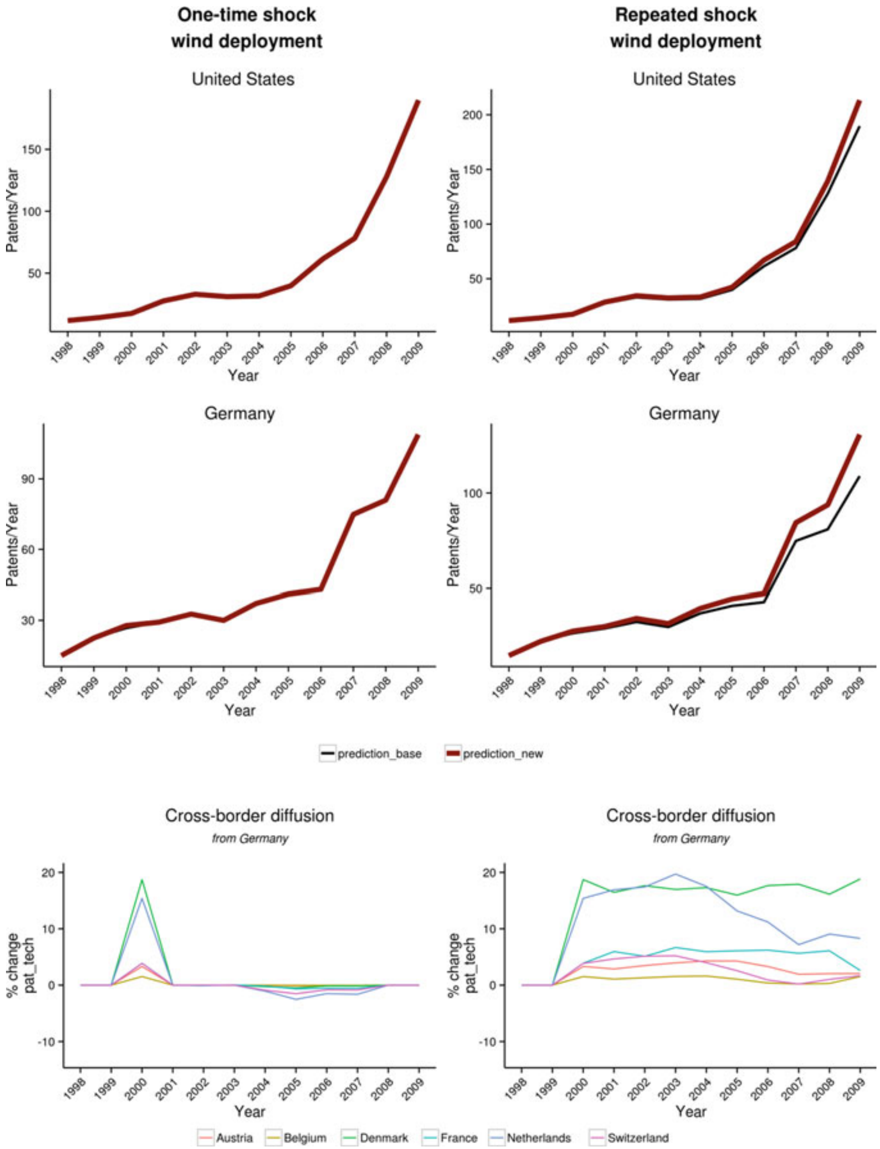
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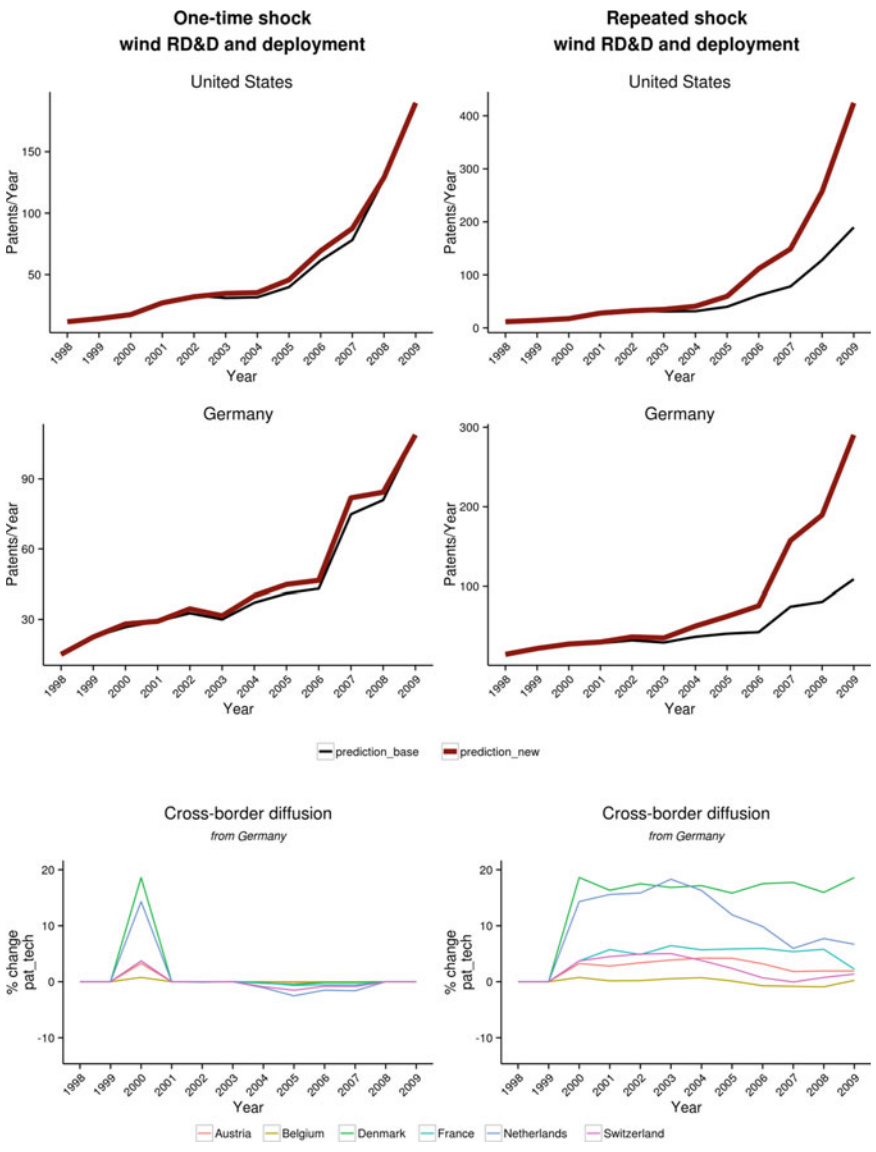

One-time shock
wind RD&D and deployment
Repeated shock
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Patents/Year
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Cross-border diffusion
from Germany
% change pat_tech
Austria
Belgium
Denmark
France
Netherlands
Switzerland

A.2 RCA Ranking Regression

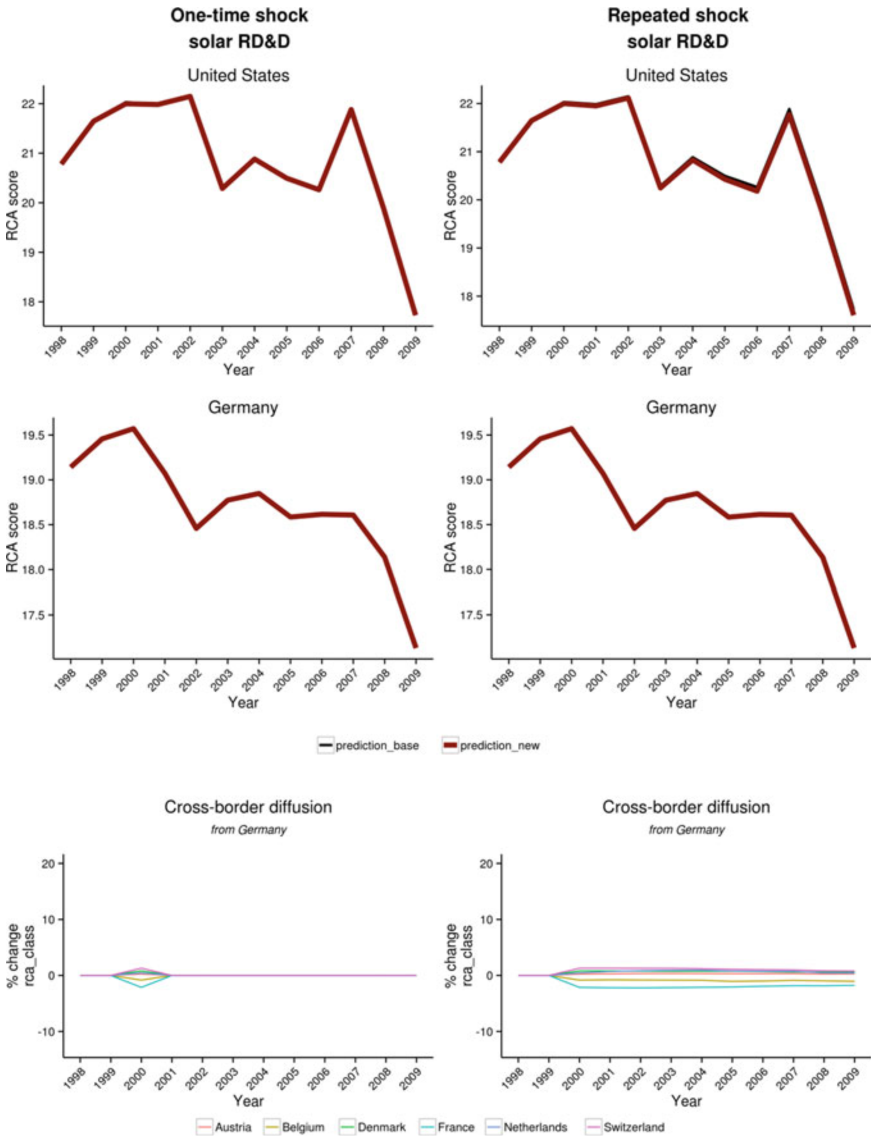
Table 9 Solar

(Intercept)	2.588
dep_solar_partsum2_lag1	0
dep_solar_partsum3_lag1	0.01
dep_total_cumulated:rdd_solar_dwdist	−0.107
pat_total_logged	0.241
rdd_res_rooted_partsum5_lag3	0.075
rdd_res_squared_lag5:rdd_solar_logged_partsum4	−0.018
rdd_res_squared_partsum4_lag2:rdd_solar_logged_partsum5_lag3	−0.001
rdd_res_squared_partsum5_lag2:rdd_solar_logged_partsum5_lag3	0
rdd_res_squared_partsum5_lag3:rdd_solar_logged_partsum5_lag2	−0.062
rdd_res_squared_partsum5_lag3:rdd_solar_logged_partsum5_lag3	−0.019
rdd_solar_dwdist:rdd_solar_dwdistwces	−0.011
rdd_solar_dwdistwces:rdd_res_rooted_partsum5_lag3	0.061
rdd_solar_logged:rdd_res_squared_lag5	−0.003
rdd_solar_logged:rdd_solar_logged_lag3	0.014
rdd_solar_logged:rdd_solar_logged_partsum1_lag2	0
rdd_solar_logged_partsum2:rdd_res_squared_partsum2_lag2	−0.022
rdd_solar_logged_partsum2:rdd_res_squared_partsum4_lag1	−0.001
rdd_solar_logged_partsum3:rdd_res_squared_partsum4_lag2	−0.013
rdd_solar_logged_partsum5:rdd_res_squared_partsum5_lag2	−0.006
rdd_solar_logged_partsum5:rdd_res_squared_partsum5_lag3	−0.001
rdd_solar_logged_partsum5:rdd_solar_squared_partsum3_lag1	0
rdd_solar_squared:rdd_solar_logged_partsum5_lag3	−0.021

Table 10 Wind

(Intercept)	2.603
continent_dep_wind	0.028
continent_dep_wind:rdd_res_rooted_lag3	0.025
continent_dep_wind:rdd_res_rooted_partsum1_lag2	0.018
continent_dep_wind:rdd_wind_partsum5_lag3	0.011
dep_total:dep_wind_dwdist	−0.009
dep_wind_dwdist:dep_total_partsum2	−0.025
dep_wind_dwdist:dep_total_partsum5	−0.003
dep_wind_dwdist:dep_wind_dwdistwces	−0.008
dep_wind_dwdist:rdd_wind_dwdist	−0.029
dep_wind_dwdist:rdd_wind_rooted_lag5	−0.033
dep_wind_dwdist:rdd_wind_rooted_partsum2_lag3	−0.008
dep_wind_dwdist:rdd_wind_rooted_partsum5	−0.052
dep_wind_dwdistwces:dep_wind_partsum5_lag3	0.02
pat_total_logged	0.159
rdd_wind_dwdistwces:dep_wind_partsum5_lag3	0.009
rdd_wind_dwdistwces:rdd_res_lag5	0.014
rdd_wind_dwdistwces:rdd_wind_partsum5_lag2	0.009
rdd_wind_dwdistwces:rdd_wind_partsum5_lag3	0.028
rdd_wind_logged_partsum2:rdd_wind_logged_partsum3_lag2	−0.006
rdd_wind_logged_partsum3:rdd_wind_logged_partsum2_lag3	−0.012
rdd_wind_logged_partsum3:rdd_wind_logged_partsum3_lag3	−0.02
rdd_wind_logged_partsum5:rdd_wind_logged_partsum4_lag1	−0.014

A.3 Solar RCA


One-time shock
solar RD&D
Repeated shock
solar RD&D
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RCA score
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Cross-border diffusion
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Austria
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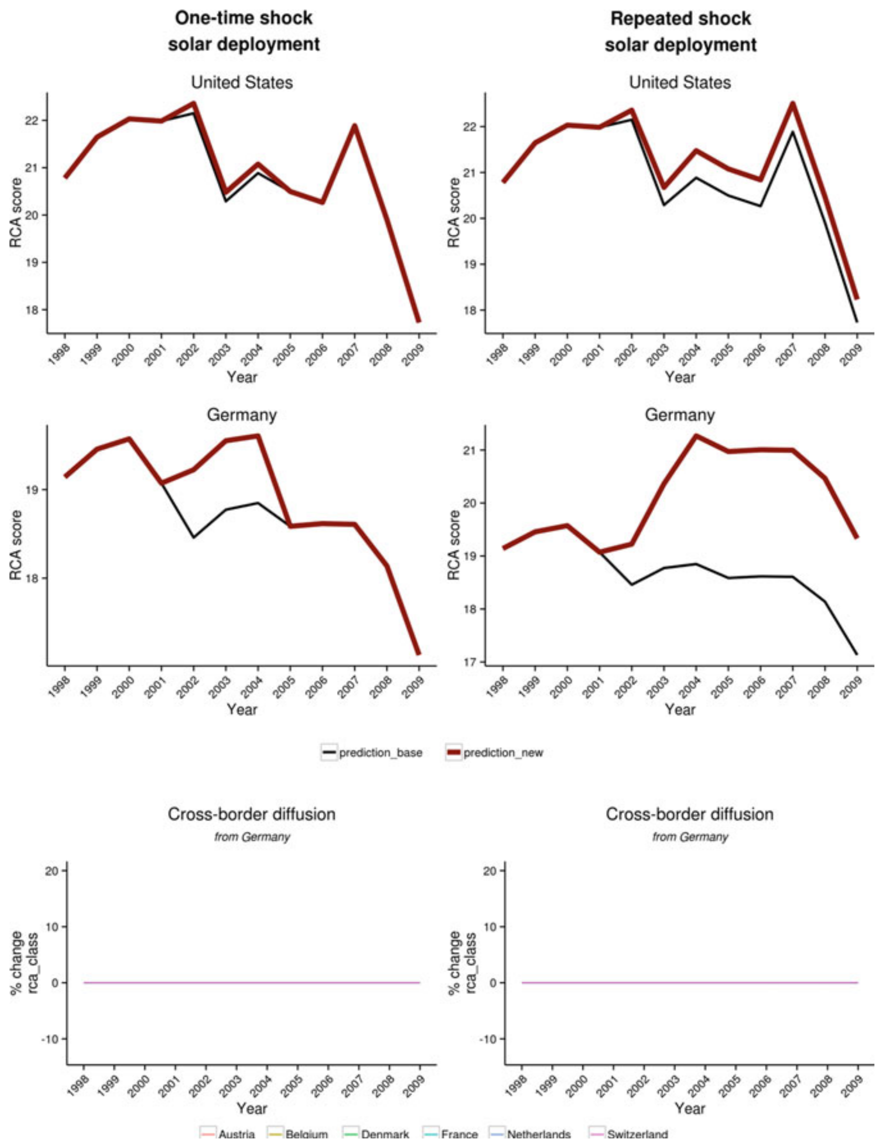
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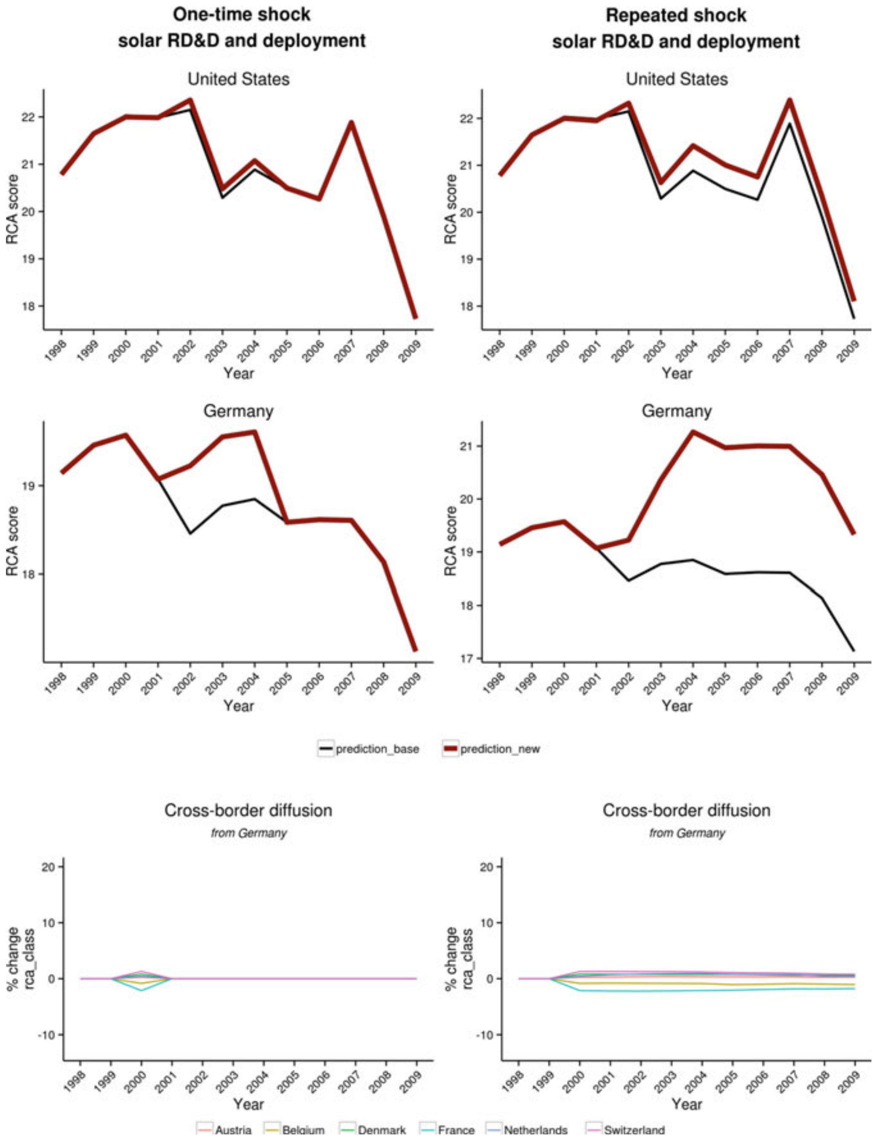
One-time shock
solar RD&D and deployment
Repeated shock
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United States
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RCA score
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Cross-border diffusion
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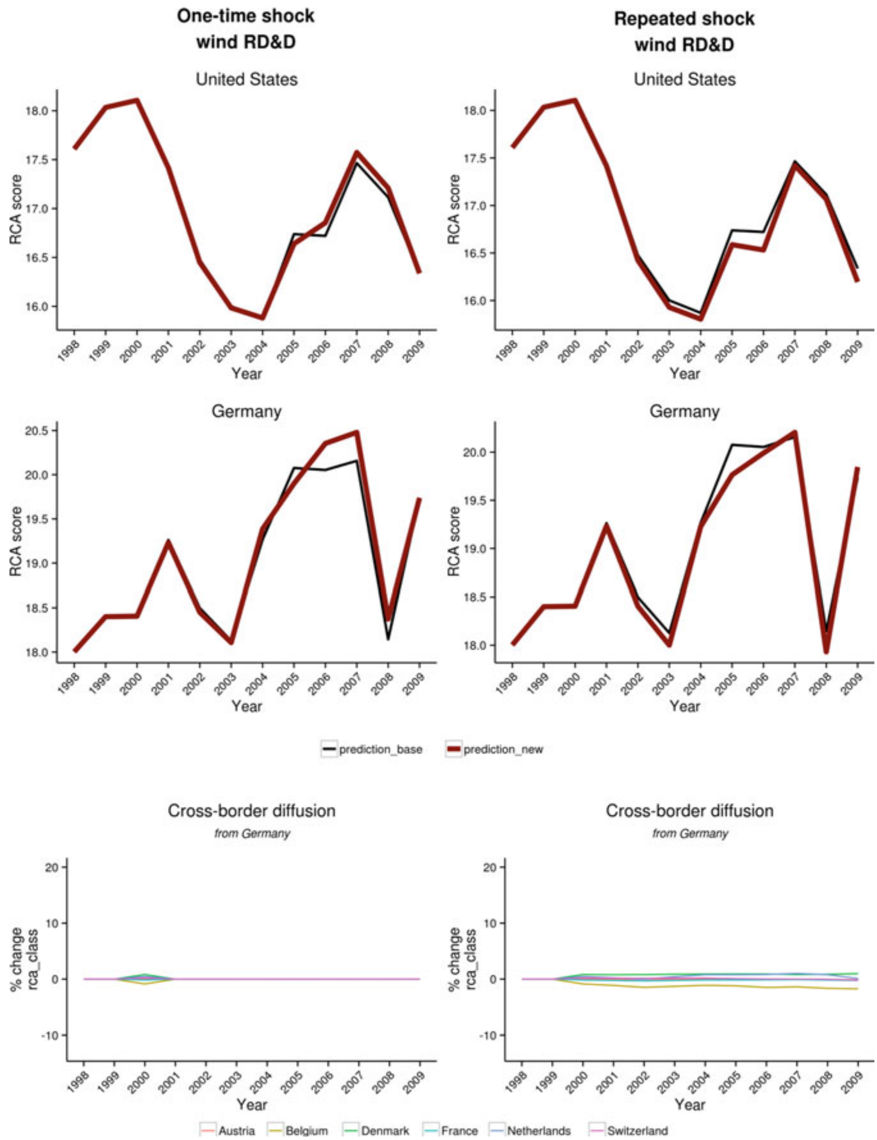
A.4 Wind RCA


One-time shock
wind RD&D
Repeated shock
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United States
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RCA score
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Cross-border diffusion
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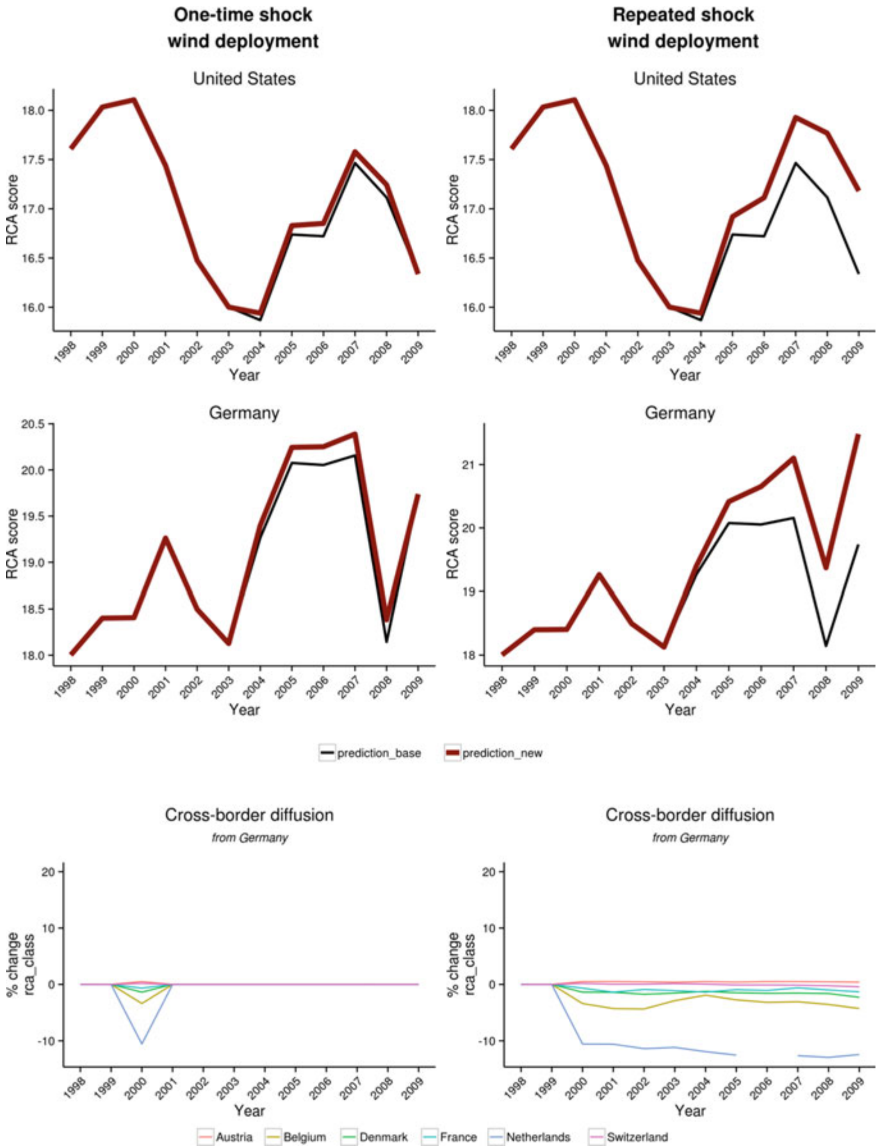
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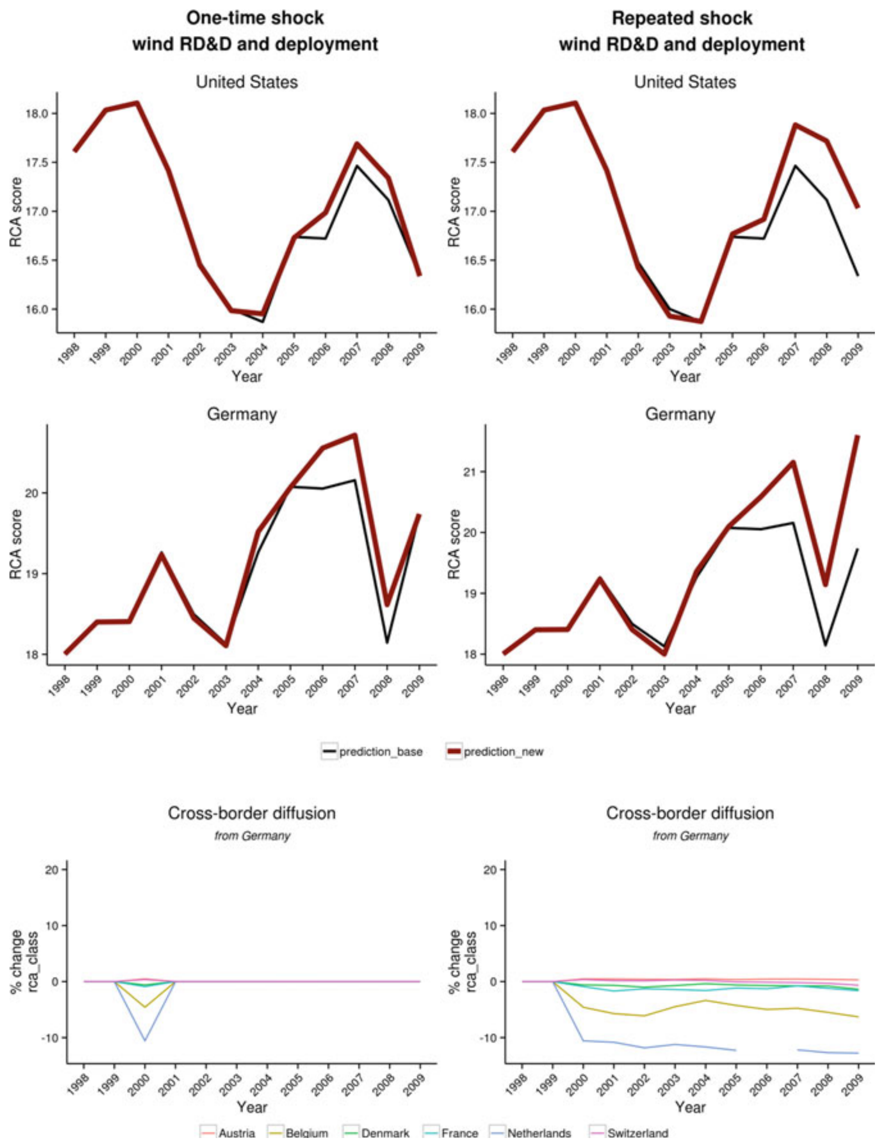

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Renewable Energy Promotion: Usual Claims and Empirical Evidence

Pablo del Río

Abstract Given the alleged environmental and socioeconomic benefits of electricity from renewable energy sources (RES-E), their public promotion has become a policy priority for governments all over the world in the past. However, in those countries with an already large penetration of renewable energy in their electricity mix, there is substantial concern about the policy costs of support for RES-E. Limiting those costs has also become a policy priority both for developed and developing countries. Academia has tried to respond accordingly, and there is already a voluminous literature on the analysis of the effectiveness and cost-effectiveness of RES-E support. This literature has been both theoretical and empirical. The later has been based on different methodologies, including case studies and model simulations. However, there are still some general claims which are largely unsupported with empirical data. Other statements are at least arguable or refutable on theoretical grounds. Based on a throughout review of the theoretical and empirical literature, the aim of this chapter is to discuss some usual claims about renewable energy promotion. The results of the analysis suggest fruitful avenues for further research on the topic.

1 Introduction

Given the alleged environmental and socioeconomic benefits of electricity from renewable energy sources (RES-E), their public promotion has become a policy priority for governments all over the world [1]. Although, in general, private generation costs are higher for renewable than for conventional electricity, the former provides benefits that are not valued by the market. Those benefits translate into a generally lower social cost (inclusive of private costs plus negative external

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costs minus positive externalities) for RES-E, but market operators (investors, generators, suppliers and consumers) are guided by the incentives provided by the market, where decisions are taken on the basis of private and not social costs (unless, of course, policy measures internalize those externalities). Public support to renewable energy levels the playing field with respect to conventional electricity, internalizes the positive externalities of renewable energy in the decisions taken by economic actors and allows renewable energy to penetrate the electricity market [2].

In those countries with an already large penetration of renewable energy in their electricity mix, there is substantial concern about the policy costs of RES-E support and limiting those costs has also become a policy priority both for developed and developing countries [3]. Governments all over Europe are concerned about the increasing expenditure on renewable energy, which is deemed unsustainable in the short-term [4]. Therefore, the cost-effectiveness of support for RES-E is a main criterion to assess the success of policy instruments, together with effectiveness, which refers to the ability of an instrument to reach a RES-E target.

Academia has tried to respond accordingly, and there is already a voluminous literature on the analysis of the effectiveness and cost-effectiveness of RES-E support. This literature has been both theoretical and empirical. The later has been based on different methodologies, including case studies and model simulations. However, there are still some general claims which are largely unsupported with empirical data. Other statements are at least arguable or refutable on theoretical grounds. Based on a throughout review of the theoretical and empirical literature, the aim of this chapter is to discuss some usual claims about renewable energy promotion and to reply to them. The results of the analysis suggest fruitful avenues for further research on the topic.

Accordingly, the rest of this chapter is structured as follows. The next section discusses eight usual claims about RES-E promotion and replies to them on either theoretical or empirical grounds. The chapter closes with some concluding remarks.

2 Usual Claims and Replies

The eight usual claims discussed in this section follow the same structure. For each of them, we first discuss their rationale and, then, immediately after, we provide a critical discussion on them ("reply"). The following table summarizes the claims and the replies (Table 1).

Table 1 Summarizing the claims and the replies

Number	The usual claim	The reply
1	A carbon price is all we need for climate change mitigation	A carbon price is not enough. Complementary policies are needed, given the existence of several market failures/ externalities. However, policy combinations are not a panacea. They bring problems of their own. They may lead to policy interactions and conflicts (redundancies, double coverage…)
2	Technology neutrality should be aimed at	Technological neutrality is hardly dynamically efficient
3	"Best instruments" should be applied	Too abstract discussion on "which is the best instrument". In the RES-E policy realm, design elements really make the difference. Furthermore, since there are several criteria, it is difficult to tell whether one instrument scores well in all criteria
4	Market-based deployment instruments are superior	Quantity-based schemes are not necessarily more "market-oriented" than price-based ones. Complying with equimarginality does not necessarily lead to a minimization of policy costs
5	R&D and deployment should be combined	Practical difficulties in finding the appropriate balance between support for R&D and support for deployment
6	The success of RES-E policies should be analyzed according to the effectiveness and cost-effectiveness criteria	Other criteria might be very relevant as well
7	Strong emphasis on harmonization versus subsidiarity of support schemes in the EU	There are other more realistic intermediate alternatives: convergence, cooperation and coordination of support schemes
8	Security for investors and stability of the support scheme should be pursued	Balance policy flexibility and stability

2.1 A Carbon Price Is All We Need for Climate Change Mitigation

2.1.1 The Usual Claim

Drastic emissions reductions will be required in order to put the world economy on an emissions concentration path which minimizes the risk of collapse of the climate system. Generally, a 2° temperature increase above pre-industrial levels is deemed compatible with this goal. In turn, this involves an emissions concentration level of

450 parts per million of CO_2 equivalent (ppm). Stabilizing concentrations at 450 ppm will require that global net emissions peak by around 2015, decline rapidly after that time, and reach zero soon after 2050 [5]. Several documents illustrate that the emissions reductions being required are substantial.[1]

As shown by model simulations (see [7, 10, 11], among others), whether emissions will be reduced and the costs of so doing will depend strongly on the availability of low-carbon technologies across different time frames. In fact, model simulations consistently show that attaining such drastic emissions reductions cost-effectively will require a mix of technologies.[2] While some technologies are already commercially available, i.e., ready to be taken from the shelf and deployed, others aren't yet commercially viable and need to mature.

In the past, some authors have argued that a carbon price is a necessary and sufficient condition to achieve the type of technological revolution that will be required. For example, one of the most renown climate change economist argues that "raising the price of carbon is a necessary and sufficient step for tackling climate change" [12], p. 22.[3] It is usually argued that a credible long-term carbon price (whether in the form of a carbon tax or a cap-and-trade scheme), which internalizes the negative environmental externality from CO_2 emissions, will increase the costs of using polluting technologies and, thus, encourage innovation and diffusion of cleaner ones [13]. This relates to the criterion of dynamic efficiency which, in practice, refers to the capacity of instruments to induce technological innovation and technology cost reductions. Dynamic efficiency is particularly relevant when there are long-term policy targets because innovation is a critical variable in achieving them cost-effectively. The carbon price is claimed to be better than command-and-control regulation (either in the form of technology or emissions standards) both with respect to economic efficiency and innovation effects. The carbon price encourages low-carbon innovations since firms subject to a carbon price have an inherent incentive to either develop or adopt technologies in order to comply with their CO_2 targets at lower costs. It is argued that this incentive/pressure is transmitted to all the stages of the innovation process and to actors involved in this process, notably equipment suppliers (see, for example, among others, [14–17].

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[1] For example, according to McKinsey [6], emissions would need to decrease by 35–50 % in the period from 2005 to 2030 to attain a pathway likely to achieve the 2 °C threshold. See [7–9], among others.

[2] For example, IEA [9] shows that, in order to achieve the 43 $GtCO_2$ of emissions reductions required by 2050, the following technologies/options should be used: CCS (expected to achieve 19 % of emissions reductions between the baseline scenario and the 450 ppm scenario), nuclear (6 %), renewable energy sources (17 %), Power generation efficiency and fuel switching (5 %), end-use fuel switching (15 %) and end-use fuel and electricity efficiency (38 %).

[3] This author, however, recently justifies direct subsidies to fund necessary research on low-carbon energy (p. 24). Later, in p. 29, the author is softer about the "sufficient condition": "placing a near universal and harmonized price or tax on carbon is a necessary and perhaps even a sufficient condition for reducing the future threat of global warming".

2.1.2 The Reply

A carbon price is an appropriate instrument to internalize the negative environmental externalities related to CO_2 emissions. However, there are other externalities (i.e., market failures) in the innovation process, i.e., an innovation and a deployment externality. There is a technological externality which is related to spillover effects enabling copying of innovations, which reduces the gains from innovative activity for the innovator without full compensation. In other words, firms are unable to fully appropriate their R&D. Basic research has especially high spill-over rates. This "innovation externality" does not only relate to R&D, but also to demonstration[4] [19]. In addition, there is a deployment externality. This is related to the increased deployment of a technology which results in cost reductions and technological improvements due to learning effects and dynamic economies of scale [20].[5] Although investors can partially capture these learning benefits, e.g., using patents or their dominant position in the market [22], the initial investor does not capture all of them. Thus, investments in the new technology will remain below socially optimal levels.[6] Of course, learning is certainly a source of innovation and cost reductions but it does not come freely. It is the result of previous investments.[7]

These two externalities provide a rationale for complementing the carbon price with additional instruments which tackle those externalities. R&D can be encouraged directly with R&D subsidies, tax credits and rebates. Demonstration can be supported with funding of demonstration projects. Finally, deployment of low-carbon technologies can be promoted directly with a wide array of instruments, including feed-in tariffs (FITs), tradable green certificates (TGCs), tendering and investment subsidies, among others (see Sect. 2.4).

The relevance of the innovation externality is very high in the first stages (i.e., research and development), and decreases as we move downstream in the innovation process, i.e., the diffusion stage where technologies are already mature (Fig. 1). In contrast, the environmental externality is relatively more important in the diffusion stage. Thus, it seems clear that in the initial and final stages, instruments should predominantly tackle the innovation and environmental externalities, respectively. The deployment externality usually plays a major role in the intermediate stages of

[4] The size and complexity of demonstrating these technologies, which often includes complex planning and infrastructural support, make it difficult for the private sector to independently finance demonstration [18].

[5] Since the 1970s, the costs of energy production from all technologies have fallen systematically through innovation and economies of scale in manufacture and use (apart from nuclear power). Technologies such as solar energy and offshore wind all show much scope for further innovation and cost-reduction [18, 21].

[6] Different types of learning effects have been considered in the literature, including learning-by-doing, learning by using and learning by interacting.

[7] In addition, there are other failures (some of them sector-specific) that might contribute to under-investment in innovation in market-only environments. These include constrained access to credit for small innovative firms, informational problems and costs and agency issues (split incentives) [6, 13]. They can vary across different technologies and sectors [7].

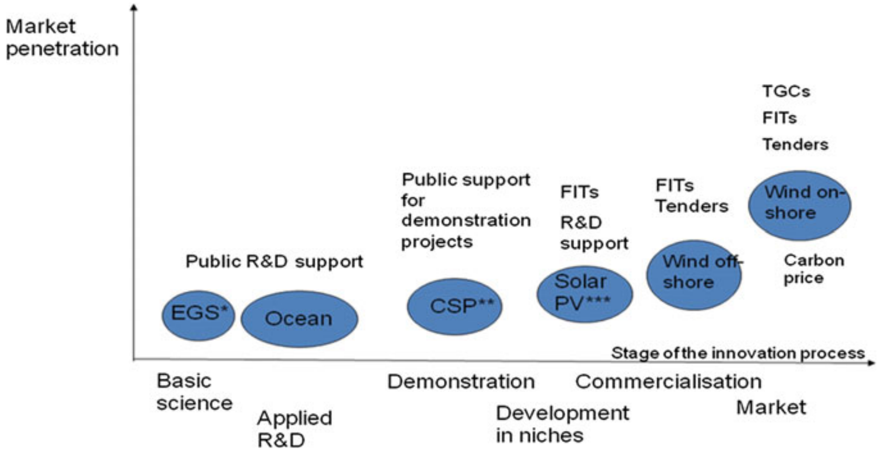

Fig. 1 Degrees of maturity of renewable electricity technologies and appropriate support instruments. *Source* Adapted from IEA [40]

the innovation process, i.e., for technologies which have passed demonstration but are in the precommercialisation stage, and even in the initial phase of commercialization, and for which a large cost reduction potential with increased diffusion exists. Therefore, the specific characteristics of the technologies have to be taken into account, i.e., their maturity level, costs, potentials for cost reductions and main sources of technological change (i.e., whether R&D or learning effects from deployment dominate).

Of course, it could be argued that a carbon price can promote the development and diffusion of technologies with different maturity levels. However, this statement would not stand empirical scrutiny. The empirical literature is quite clear in this regard. It shows that the impact of the carbon price in the European Union Emissions Trading Scheme (EU ETS) on radical innovation is likely to be very limited [23–29] also show that the US Acid Rain program did not encourage…"also show that the US Acid Rain program did not encourage significant innovation. Taylor et al. [29] did not find evidence that the ETS within the Acid Rain program promoted innovation in a more effective manner than other instruments. Malueg [30] and Driesen [31] have criticized the common argument that emissions trading schemes promote innovation to a greater extent than other instruments. They claim that, while potential sellers of permits (i.e., those with the lowest abatement costs) have an incentive to innovate in order to sell permits and earn a profit, an emissions trading scheme reduces the incentive to innovate compared to standard regulation for those polluters with high abatement costs. Under traditional regulation these firms would have an incentive to innovate in order to comply with regulation. Under an ETS, this incentive would be lost since they just would buy the permits.

Of course, it might be argued that the EU ETS allowance price has been too low and volatile. But this is exactly the point: it has been too low because, apart from the economic crisis, countries were relatively generous in the allocation of allowances in order to mitigate the economic burden on their own firms [32, 33]. Political economy considerations and the institutional path dependency approaches suggest that CO_2 prices are unlikely to be set at a sufficiently high level to trigger (radical) low-carbon innovation,[8] as shown by the low EU ETS allowance price in the first and second commitment periods.[9] High carbon prices are unlikely to be politically feasible since a national hard climate policy is politically unprofitable, i.e., it does not help to win votes and may lead to loss of competitiveness and leakage by the country adopting such a policy.

The above does not argue against the use of a carbon price to trigger the development and diffusion of low-carbon technologies. It is a necessary albeit not sufficient element in the required policy mix. A carbon price can not cover everything and can not address all relevant externalities. Policies to specifically support the innovation and deployment of renewable energy technologies might be justified taking into account the aforementioned three externalities.

However, policy combinations are not a panacea and bring problems of their own. They may lead to policy interactions between them, which might be positive or negative. One example of a negative interaction (conflict) might be the case of ETS and renewable energy support (see [35] for further details).

2.2 *Technology Neutrality Should Be Aimed at*

2.2.1 The Usual Claim

Somehow related to the previous point, some authors argue in favor of “technology-neutral policies”, i.e., instruments which may lead to the choice of the cheapest technologies. It is claimed that, since governments do a poor job in “picking winners”, the choice of technologies should be left to “market forces”. Government failure may lead to lock-in in inappropriate, expensive or simply bad technologies. This argument has been used to criticize direct public support to the deployment of renewable energy technologies (see, e.g., [36]).

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[8] For an overview of these approaches applied to climate change mitigation and low-carbon technologies, see del Río and Labandeira [34].

[9] During the first compliance period (2005–2007), the EU allowance price reached a peak near 30 € in mid 2006, declining gradually to near 0€ in February 2007 and remaining at such level for the rest of 2007. In the second compliance period (2008–2012), the price reached a peak near 30€ in early 2008 and then stabilized at around 15€ for most of the rest of the period, declining to around 8€ by the end of it.

2.2.2 The Reply

Technology neutrality is hardly dynamically efficient. This is so because in a problem with such a long-term horizon, such as climate change mitigation, we need to put technologies on the shelf (i.e., promote their development), not only to take them from the shelf (i.e., promote their diffusion) [37]. A technology neutral instrument, such as a CO_2 price, would only allow for the later but not for the former. In particular, policies need to bridge the gap with respect to the aforementioned valley of the death between discoveries in the lab and the large-scale deployment of commercial products. It is hard to see how this can be done without a technology-specific policy. Technology-neutral policies would only favor currently mature technologies, but they would not provide a sufficient stimulus for the development and diffusion of currently more expensive less mature technologies with a large cost-reduction potential. As argued by Azar and Sanden [38] "If the aim of governments is to reduce CO_2 emissions, policies explicitly aiming to develop carbon efficient technologies will by definition be technology-specific".

Therefore, while technology-neutral policies aim at static efficiency, dynamic efficiency requires the implementation of technology-specific policies. Thus, the debate about whether these policies should be technology-specific becomes rather meaningless, and should be replaced by a discussion about how technology-specific the policies should be [38]. The dilemma about applying technology-neutral versus technology-specific policies may suggest a broader trade-off between the static efficiency and dynamic efficiency criteria and also between market failure and government failure in the choice of low-carbon technologies. Further research should be devoted to the analysis of those trade-offs and appropriate balances between the two.

2.3 "Best Instruments" Should Be Applied

2.3.1 The Usual Claim

A voluminous literature has compared the pros and cons of different instruments to support RES-E. The focus has mostly been on "quantity-based schemes" (TGCs) versus "price-based instruments" (FITs).

- FITs are subsidies per kWh generated, combined with a purchase obligation by the utilities.
- Quotas with TGCs (called Renewable Portfolio Standards (RPS) in the US) are certificates issued for every MWh of RES-E, allowing generators to obtain additional revenue to the sale of electricity (i.e., two streams of revenue). Demand for TGCs originates from an obligation on electricity distributors to surrender a number of TGCs as a share of their annual consumption (quota). Otherwise, they would pay a penalty. The TGC price strongly depends on the interaction of supply and demand and other factors.

There are other instruments which have received less attention in comparative analyses, including investment subsidies and tendering.

- Investment subsidies are usually granted per unit of installed capacity (i.e., €/MW), i.e., not generation (i.e., €/kWh).
- Tendering/bidding systems. The government invites RES-E generators to compete for either a financial budget or RES-E generation capacity. Within each technology band, the cheapest bids per kWh are awarded contracts and receive the subsidy (i.e., bid price per kWh).

The comparative analysis of RES-E support schemes has focused on the FITs versus TGCs dichotomy, probably reflecting the fact that these two have in the past been the two main instruments on which Member States have based their support schemes. These instruments have been compared on the basis of the effectiveness and cost-effectiveness criteria (see Sect. 2.4).

2.3.2 The Reply

In our view, the RES-E literature has been trapped into "instrumentalism", often times providing a too abstract, blackboard discussion on "which are the best instruments". Only recently have researchers stressed that the devil lies in the details and that the success or failure of instruments applied in the real world mostly depend on their design elements, i.e., intra-instrument differences may be as important as inter-instrument ones. This has been clearly shown in empirical analyses (see [39–42]). We should be particularly careful in avoiding biased analyses, in which a "well designed instrument 1" is compared to a "badly designed instrument 2" and conclusions are inferred about the instruments, leading to the wrong interpretation that the later instrument is worse than the former, when the difference really lies in the particular design elements being chosen. Finally, the focus on FITs and TGCs should cease and the suitability of other instruments should also be assessed. In particular, tendering/bidding schemes are a good candidate in this regard, since, as with FITs, but in contrast to TGCs, both ensure a reliable, long-term income for renewable energy investors and they also allow regulators to know in advance the level of support being awarded. However, under tendering schemes, the total amount of support provided can be more easily capped than under either FIT or TGCs, allowing investors to compete until the whole budget is gone.[10] In addition, auctions deal better with the asymmetric information problem, i.e., they perform better than FITs when trying to know the true level of support required, especially for those technologies with large uncertainties about their cost trends, like off-shore wind. Auctions reveal better the reduction in the

[10] It can be argued that, since RES-E generation is capped under TGCs, the total amount of support would also be capped. However, this is not the case, since total support depends on the amount of RES-E generation times the level of support, which depends on the a priori unknown interactions between the demand and supply sides in the TGC market.

costs of technologies over time and allow the support to be adapted accordingly. This ideally brings more efficiency into the system by preventing RE producers to be overcompensated. It also encourages competition between RES-E generators. Banded bidding schemes with pay-as-bid mechanisms allow support to be tied to generation costs, in contrast to TGC schemes (whether banded or not) [43]. The fact that they are only modestly being applied in Europe might be a reflection of the fact that previous experiences in Europe have been rather disappointing (see [43] for further details). However, these experiences (in the U.K., Ireland and France) were probably disappointing not because of inherent flaws in the instrument, but because the design of the schemes was not the appropriate one, which confirms the relevance of taking the design elements of the scheme into account.

2.4 Market-Based Deployment Instruments Are Superior

2.4.1 The Usual Claim

There is a general presumption among environmental economists that market-based instruments work better than non-market-based ones (see [12]). In the RES-E policy realm, the former are generally identified with quotas with TGCs, while FITs are usually not considered a market-based instrument. TGCs are presumed to work better regarding cost-effectiveness (compliance with a given RES-E target at the lowest possible costs) because they interfere less with the market since the level of support (i.e., the TGC price) would be set in the TGC market and this would automatically lead to "cost-effectiveness" [44]. In contrast, under FITs, remuneration levels would be set by the government. TGCs comply with the first equimarginality principle, which is not necessarily the case under FITs. According to Tietenberg [45], an environmental target is achieved at the lowest costs when the marginal costs of all possible means of achievement are equal.

The following table (Table 2) provides a simple illustration of the equimarginality rule. We consider three renewable energy technologies, all with increasing albeit different marginal costs (i.e., worst locations in terms of a specific renewable energy resource are more costly). Assume that the government sets a RES-E target of 21 MWh. The costs of complying with the target are minimized (429€) when the marginal costs for all three technologies are equal, i.e., at 39 €/MWh. The different technologies contribute differently to this target: the lowest cost technology (B) contributes more than the other, more expensive technologies (i.e., 9 MWh for technology B versus 8 MWh for technology C and only 4 MWh for technology A). The costs of attaining the 21 MWh target would be significantly higher (487€) if all the technologies contributed to the same extent.

In principle, a TGC scheme would ensure that the equimarginality principle is complied with (at a TGC price of 39 €/MWh). This is not the case under FITs, since the government would need to set the remuneration level at exactly 39 €/MWh. However, this is difficult, since it would need information on the marginal cost curves, which might not necessarily be the case.

Table 2 Illustrating the equimarginality principle

MWh	Marginal costs (€/MWh)		
	Technology A	Technology B	Technology C
1	5	3	27
2	7	4	30
3	10	6	34
4	14	9	*39*
5	19	13	46
6	25	19	55
7	*32*	*24*	*66*
8	*39*	31	79
9	49	*39*	94
10	59	48	111

Source Own elaboration

2.4.2 The Reply

Apart from the fact that it is rather simplistic to compare instruments between each other in an abstract setting, without considering their specific design elements (see Sect. 2.3 above), it is arguable whether TGCs are "more market-based" than FITs. From an environmental economics point of view, this is not correct.

A classical distinction in environmental economics regarding policy instruments is that between command and control (CAC) and market based instruments (MBI) [46, 47]. The later can be further classified in quantity-based and price-based instruments. Cap-and-trade schemes and TGCs are examples of the former, whereas taxes and FITs are examples of the later. In environmental economics, quantity-based instruments are not regarded as inherently superior. Thus, apart from the fact that TGC schemes create a market in which TGCs can be traded, there is no reason to claim that "TGCs are more market-based" and, thus, superior, at least not under an environmental economics perspective. More importantly, while it is true that TGCs are in theory more likely to comply with the equimarginality principle, this does not ensure that policy costs are minimized under this instrument, or even that they are lower than under FITs. Indeed, empirical research has shown that the opposite is true, i.e., that the policy costs of FITs are generally lower than those of TGCs [3, 42, 48–50]. In theory, remuneration levels under FITs can be adjusted to the costs of the technologies (technology-specific support). In contrast, under a technology-neutral instrument such as TGCs, support is uniform for all technologies (given by the TGC price). This TGC price is set by the marginal costs of the last technology needed to comply with the target. This results in high remuneration levels for the most mature, cheapest renewable energy technologies, i.e., for those technologies with costs below the TGC price. However, this conclusion neglects two major points. On the one hand, it might be difficult for the government in the real world to set the support levels close to the generation costs of each technology. On the other hand, this analysis falls into the "instrumentalism" trap (see Sect. 2.3), since some design elements under TGCs are available (credit multipliers and carve-outs) to adapt the support levels to the costs of electricity generation by each technology.[11]

In addition, when a dynamic efficiency perspective is adopted, it becomes even clearer that TGCs are not superior. FITs have proven superior since they are able to support technologies with different levels of maturity and costs, and not only the cheapest ones (see [51]). This facilitates innovation through the advancement of technologies along their learning curves (through their diffusion) and private R&D investments, given the existence of a market for renewable energy technologies and profitability levels which allow the benefits to be reinvested (although not necessarily) in R&D. Under a quota with TGCs, the most expensive technologies are not supported (i.e., those technologies whose costs are above the TGC price), as shown by Verbruggen [52] and Bergek and Jacobsson [53] for Belgium and Sweden, respectively. This is due to the high revenue uncertainty levels (due to the volatile TGC price) and the very low producer surplus for investors in immature technologies (if any surplus at all), which makes it extremely difficult to invest in R&D.

2.5 R&D and Deployment Should Be Combined

2.5.1 The Usual Claim

Learning-by-doing (LBD) and R&D investments are two main sources of technological change. The former refers to repetitious manufacturing of a product leading to improvements in the production process and costs reductions in the technologies. Both factors allow technologies to improve their quality and reduce their costs and are complementary in addition to carbon prices [54]. Some authors argue that, with respect to some technologies (mostly solar PV), too much public support has been dedicated to deployment and less than what would have been socially optimal has been devoted to R&D [37]. There seems to be a widespread consensus that past and current levels of public (and private) investments in renewable energy R&D are too low to address energy-related concerns, including climate change [55].

Data on government energy RD&D (research, development and demonstration) expenditures in IEA countries show that a peak was reached in 1980, then it declined and reached a minimum in 1997. The later increase allowed such expenditure in 2009 to be at the same level as in 1980 in absolute terms, although it was reduced, again, in 2010 [56]. Likewise, R&D expenditures in renewable energy peaked in the 1980s,

[11] Under carve-outs, targets for different technologies exist, leading to a fragmentation of the TGC market, with one quota for the mature and another for the non-mature technologies. Under credit multipliers, more TGCs are granted per unit of MWh generated for immature technologies compared to mature technologies. The alternative is no use of carve-outs or credit multipliers, such as in the Swedish and Polish TGC schemes [40].

declined and peaked at a higher level in 2009. According to OECD [57], public spending in renewable energy RD&D in OECD countries represented in 2007, 25 % of total public energy technology RD&D and was at the same level than in 2000.

The bulk of public R&D expenditures in renewables in IEA countries is currently dedicated to solar PV (about 35 %, 542 million USD in 2010) and wind (about 30 %, 424 million USD) [56]. Expenditures on CSP, ocean, geothermal, hydro and bioenergy are very similar (in the range of 101–130 million USD each) [56]. These R&D expenditures are clearly lower (in fact, a very small fraction) than expenditures on deployment, i.e., compare those figures with the US$ 66 billion of global subsidies to renewable power world-wide [58].[12]

2.5.2 The Reply

Some economists are skeptical about the existence of a deployment externality and, thus, they only justify a carbon price and R&D support and are critical direct deployment support (see, e.g., [37, 60]). However, R&D spending without the acquisition of experience through deployment that involves learning will make the technology harder to implement on a wide scale [61].

While it is obvious that a combination of deployment and R&D is needed, the question remains as to the appropriate balance between the two. This certainly depends on the level of maturity of the technologies, i.e., it is a technology-specific issue. In general, for immature technologies, cost reductions and technology improvements are more closely related to R&D investments and R&D support. In contrast, improvements in the technology and cost reductions achieved in the laboratory are limited for mature technologies. But, to the best of our knowledge, there is no study indicating the optimal share of funds that should be dedicated to either R&D support or deployment support in order to encourage the greatest technology cost reductions per € of support. Further research should clarify, for each technology, what the balance should be.

In addition, both deployment and R&D have been treated as if they were isolated from each other when in reality they interact in complex ways. There are positive feedbacks between the two. RD&D lead to cost reductions, make the technologies more attractive for potential adopters, encourage diffusion and, thus, reinforces advancements of technologies along their learning curves [53, 62]. Learning effects as a result of deployment reduce costs and promote diffusion, leading to more dynamic markets for renewable energy technologies. In turn, market creation makes RD&D investments in those technologies more attractive.[13] Indeed, empirical

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[12] For example, public R&D support for renewable energy technologies in Spain was 6.8 M€ for solar PV and 6.3 M€ for wind in 2009, whereas net deployment support for these technologies reached 2629 M€ for solar PV and 1619 M€ for wind [60].

[13] For example, Gillingham et al. [63] and Ek and Söderholm [64] note that if production costs fall, the potential competitiveness of the technology increases, increasing also the return on additional private RD&D efforts. This will induce more RD&D expenses on the part of private

studies have shown that private RD&D investments are an important side-effect of deployment policies [18, 62, 65], in a context of relatively modest and stagnant direct public RD&D support in renewable energy technologies [64, 66]. Private RD&D account for a large share of total RD&D in the RES-E sectors.[14]

Of course, there might also be conflicts. Deployment may crowd out private R&D. For example, according to Hoppmann et al. [68], FITs incentivized German firms to shift resources toward new production capacities and away from long-term R&D. More research needs to be carried out on this issue, however. The mutual interactions between both types of innovation sources should be taken into account when setting support levels in both realms. In addition, deployment support is no substitute for public RD&D support and the other way around. They are rather complements and should be coordinated.

2.6 The Success of RES-E Policies Should Only Be Analyzed According to the Effectiveness and Cost-Effectiveness Criteria

2.6.1 The Usual Claim

The criteria of effectiveness and cost-effectiveness have traditionally been used in environmental economics to assess environmental policies. These have been considered the main, and most often, the only criteria. The former refers to the ability of an instrument to reach a RES-E target, whereas cost-effectiveness refers to attaining such a target at the lowest possible cost (see Sect. 2.4).

2.6.2 The Reply

While effectiveness and cost-effectiveness are obviously key criteria to assess RES-E support schemes, other criteria are also policy-relevant, i.e., policy makers usually take them into account and, thus, they should be used in order to assess the success of policies implemented in the real world.

First, even the cost-effectiveness criterion as it has so far been used in empirical research has not taken into account two main aspects. One is transaction costs. The transaction costs related to the implementation and functioning of a RES-E support

(Footnote 13 continued)
market actors, something which in turn implies lower costs and higher market penetration rates for the technology.

[14] Criqui et al. [67] report that over the last 25 years (1974–1999) private RD&D expenditures for wind energy might have been approximately 75 % higher than public RD&D expenditures. IEA [66] notes that private-sector RD&D spending on energy technologies today is at $40–60 billion a year, about four to six times the amount of government RD&D.

scheme should also be included in the definition of cost-effectiveness. We should distinguish between system installation, system operation and system adjustment [69]. Transaction costs may fall on the public administration or on companies. The former are usually called "administrative costs" [51]. This should be a main component of the cost-effectiveness criterion and, indeed, a RES-E policy which complies with the equimarginality principle at relatively low policy costs may still be inefficient if its implementation or functioning become burdensome in administrative terms, leading to high administrative and/or transaction costs. It is indeed quite surprising that analyses which take into account these transaction costs are virtually non-existent.

On the other hand, analyses on the cost-effectiveness of support have quite often disregarded the total policy costs of complying with a RES-E target. For example, one of the most well-known assessments of these policies, carried out under the EU-funded OPTRES and RE-SHAPING projects (see, respectively, [42, 50]) compare the unitary costs of support (i.e., €/MWh) for different types of policies. However, governments in countries with either an already significant penetration of RES-E or a recently large increase in RES-E deployment are concerned about the total costs of the policy, i.e., unitary support costs times the level of deployment. The solar PV booms in several European countries is a case in point. For example, net support in Spain for solar PV increased 13-fold between 2007 and 2009, from 194 to 2629 M€, although the unitary costs of support only increased from 39 €/MWh in 2007 to 42 €/MWh in 2009. This has certainly put a burden on electricity consumers which has led to policy measures aimed at reducing those total costs (see [70] for further details). If these total costs become a priority for governments, instruments and design elements should be adopted with in-built cost-containment mechanisms. For example, in this context, bidding schemes with a total budget allocation are superior to FITs without capacity caps or limitations on the electricity generated which is eligible for remuneration.

On the other hand, there has been much focus on static efficiency and much less so on dynamic efficiency which, as mentioned above, refers to the capacity of instruments to induce technological innovation and technology cost reductions.[15] If only the currently best or cheapest technologies are promoted by supporting their diffusion, this will not allow currently more expensive technologies to penetrate the market. If currently expensive mitigation technologies have a large cost reduction potential with increased diffusion (as shown by several studies for energy technologies, see for example [66], then supporting them today would lead to welfare benefits in terms of intertemporal mitigation efficiency (i.e., cost-effectiveness in the short, medium and long terms). In contrast to cost-effectiveness, dynamic efficiency provides an intertemporal perspective on costs [51]. There is, thus, a risk of lock-in in the current technologies with detrimental economic consequences in the long term.

Not withstanding, it is arguable whether the dynamic efficiency criterion is useful for national policy-makers. Reductions in the costs of the technologies as a result of deployment or public R&D support is certainly relevant to reach supranational targets cost-effectivelly. But such support is provided mostly at a national level. Why

[15] Midtum [71] and del Río [19] are some exceptions.

should any country spend too much in this regard when the benefits in terms of cost-reductions spill to other countries?[16] This provides a rationale for supranational deployment instruments and R&D support schemes. Of course, if there was a local learning component, then some of those benefits could be appropriated by the supporting country. But, to our knowledge, an analysis of the degree of the local appropriability of learning investments does not exist, which certainly indicates a fruitful avenue for further research.

Third, other criteria are taken into account by policy makers when implementing new or reforming existing support schemes, including equity, social acceptability and political feasibility. These criteria are interrelated to some extent. Equity refers to the distributive impacts of the instruments, which may have more or less beneficial effects on different countries and actors within those countries. RES-E support and other policies may not be socially acceptable and may be rejected by the population. Social rejection may have a broad character (i.e., civil society is against the deployment of renewables or against deployment support) or a local component (i.e., the not-in-my-back-yard syndrome). Therefore, social acceptability and political feasibility go hand-in-hand. There is a surprising lack of research on the equity impacts and political feasibility of existing and proposed RES-E support schemes ([3, 72] represent two notable exceptions in this regard).

Of course, the effectiveness and cost-effectiveness of support are two main criteria to judge the political feasibility of instruments and design elements (i.e., ineffective or costly instruments are attractive for policy-makers), but they are simply not sufficient to assess the possible success or failure of proposed instruments for RES-E support. Obviously, assessing social acceptability and political feasibility goes beyond the traditional frontiers of economics (except for political economy analyses) and should be addressed by sociologists and political scientists as well. Analyses based on multicriteria decision analysis techniques would be highly appropriate in this context. This methodological tool has scarcely been used in previous research (a notable exception is [69]). Finally, when several criteria have been considered, they have been isolated from each other. In reality, they interact and, thus, trade-offs are unavoidable, i.e., improvements in one criterion may only come at the expense of worsening other criteria (see [51] for further details).

2.7 Strong Emphasis on Harmonization Versus Subsidiarity of Support Schemes in the EU

2.7.1 The Usual Claim

There is an old debate in the EU about the advantages and disadvantages of harmonizing the support schemes (see [40, 73, 74]). Harmonisation can be defined as

[16] Of course, there are other local benefits of supporting RES-E, including reductions of local pollutants and a lower dependence on foreign fossil-fuel resources.

the top-down implementation of common, binding provisions concerning the support of RES-E throughout the EU [75]. In practice, it refers to a single RES-E support scheme being applied EU-wide. In contrast, Member States may remain in charge of their national RES-E support schemes, in line with the subsidiarity principle.[17]

It is argued that harmonization brings several advantages [76, 77]:

- The internal market and the objective of its extension is a fundamental part of the 'Acquis Communautaire' and it is the EU's goal to work toward its completion. It is therefore a logical step forward to create an internal market for energy, including renewable energy. Deviations from this overarching goal could pose not only economic, but possibly also legal challenges.
- A single EU-wide support scheme would lead to an optimized allocation of resources and, thus, cost-savings. RES-E would be produced at the most optimal places with e.g., highest solar irradiation or wind speeds.
- A single market would lead to more competition and innovation.
- A larger market reduces transaction costs for RES-E investors and leads to economies of scale, triggering additional investments in renewable energy.
- Harmonized European support schemes and/or targets are more effective and easier to enforce, at least compared to national support schemes of countries lagging behind.

However, other authors are more critical about the benefits of harmonization [76], see also [73, 77]:

- Uniform support payments across Europe could lead to higher rents for those producers which make use of least-cost technologies and sites. This could lead to a substantial increase in target achievement related costs for society (tax payers or consumers).
- Each Member State (MS) has different geographical, legal, political, and market conditions in which RES-E support schemes operate. These contextual conditions would either need to be harmonized (which is only possible to some extent) or the remaining differences would need to be sufficiently reflected in a harmonized support scheme. A lack of context-specificity could decrease the effectiveness and efficiency of support.
- In order to obtain public acceptance in MSs for a harmonized support scheme, a politically accepted distribution of costs and benefits would have to be achieved, which is likely to pose a significant challenge, given the large number of MSs and their national preferences.
- Domestic energy policy and different policy interests make harmonisation difficult to achieve.

[17] Member States have developed their own tailor-made energy policies, which include different goals, ambitions and preferences. Not all Member States share a comparable ambition toward renewable energy and they are not willing to transfer the required competences to a European level [76], p. 15.

2.7.2 The Reply

The debate on harmonization has been mostly polarized, arguing either in favor or against harmonization. However, the dichotomy "harmonisation" versus "national support schemes" is outdated. It neglects the existence of more realistic alternatives in the middle. These include, but are not limited to, increased cooperation and collaboration between Member States regarding their support schemes.

Gephart et al. [73] provide the following definitions of these intermediate alternatives:

- 'Convergence' simply means that policies become similar in different Member States. Klessmann and Lovinfosse [78] and Gephart et al. [73] have shown that there has been four converging trends between the support schemes in the EU: (1) Use of combination of instruments instead of one size fits all (e.g., FITs for small scale plants and auctions for offshore wind); (2) Diffusion of feed-in premiums across Europe as compromise between revenue security for investors and RES-E exposure to market signals. (3) Moratoriums and uncertainties on the future of support schemes because of public deficits (e.g., Spain, Portugal, Latvia, Bulgaria, Czech Republic). (4) Joint support schemes (e.g., Sweden and Norway). Coordination and Cooperation lead to convergence.
- Coordination might refer to knowledge exchange between governments and possible alignment of certain elements of a support scheme.
- Cooperation either refers to governments loosely working together or it might refer to the RES Directive (2009/28/EC) and its inherent possibilities to establish statistical transfer of renewable energy, joint renewable energy projects (among MSs or with third countries) or joint support schemes as specified in Articles 6, 7, 9, and 11 of the Directive.

The European Commission initiated the debate on harmonization with the publication of the 1996 Green Paper on Renewable Energy (COM(96) 567 final) and it has traditionally been an advocate for harmonization. However, facing opposition from the majority of MSs and the European Parliament, the political debate has moved from harmonisation toward coordination and cooperation between MSs [76]. The European Commission itself supported the existence of different instruments in the different Member States in its 2008 Communication. This is currently the approach followed in Europe according to the RES Directive (Directive 28/2009/EC). The recent Communication from the Commission in June 2012 (COM(2012) 271) stresses the need for improved support schemes and calls for guidance on best practices, convergence and cooperation rather than harmonization [76].

Those intermediate alternatives have shown to be more cost-effective than either harmonization or isolated national instruments [48, 78, 79]. These authors show that the support costs of reaching the EU 2020 target with strengthened national policies (41 billion €/year) would be 25 % lower than with a uniform EU support level. More recently, Resch et al. [76] show that strengthened national RES policies complemented by moderate to strong cooperation and coordination appear suitable to keep RES well on track for reaching moderate to strong deployment targets for

2030. Related support expenditures can then be maintained on a comparatively low level (at 22.8–23.5 billion € as yearly average for new RES-E installations) while uniform RES support in a harmonized RES trading regime (without banding) may lead to a much high consumer burden (38.3 billion €).

The coordination of RES-E remuneration schemes and market frameworks across national borders can deliver a number of benefits: increased stability and transparency for investors, economies of scale, increased competition, and improved exploitation of resources. In consequence, European coordination can trigger additional RES-E investments while lowering the overall costs of RES-E deployment. On the other hand, it is important to protect the flexibility of RES-E policies to be able to adjust to local framework conditions. A lack of context-specificity can undermine the ability of remuneration frameworks to overcome local market barriers and can lower their public acceptance [80]. How increased cooperation and coordination leads to increased convergence of the most important aspects of effective and efficient support represents a fruitful avenue for further research.

2.8 Security for Investors and Stability of the Support Scheme Should Be Pursued

2.8.1 The Usual Claim

A general mantra in the RES-E literature is that a stable investment climate should be guaranteed in order to ensure investor security and, thus, promote RES-E investments. From a long-term RES-E investment perspective, stop-and-go policies are highly detrimental and, thus, abrupt or retroactive changes that destroy confidence and disrupt markets should be avoided [80]. Retroactive regulatory changes should be understood as changes in the existing remuneration conditions, which negatively affect the revenue certainty of operating plants. Once a generator locks into a given rate, the policy should not be backwardly and arbitrarily readjusted to amend the economic conditions. Otherwise, this would create insecurity for investors, making further investments unattractive. The relevance of legal security and policy stability for, both, international private entities (e.g., international utility and energy companies, international investment banks and funds, international renewable energy project developers) and public entities (e.g., development banks, government ministries) has been empirically demonstrated for emerging economies [81].

2.8.2 The Reply

While it is difficult to argue against the virtues of policy stability, what is exactly that should be stable? Taken to the extreme, one could argue that the support scheme should not be changed at all. If interpreted in this way, policy stability would have a very negative side: this rigidity may lead to problems (in terms of effectiveness or cost-effectiveness) when events do not develop as expected (i.e., material costs increase or decrease to a greater extent than expected). Obviously an inherent trade-off between policy stability and flexibility exists and a balance has to be struck between the two. The challenge will be to maintain investor confidence in market stability while managing the overall costs of policies [3]. Retroactive changes should be avoided, but policy changes for new RES-E investments should be allowed. Changes to the policy framework over time should be gradual and predictable.

Past experience has shown the importance of the ability to promptly adjust RES-E support schemes in response to changing conditions. When investment costs go down more rapidly than expected, an inability to readjust the level of support leads to excessive investors rents, excessive costs for the consumers and an overheating of the market, reducing the political feasibility of RES-E support. In other words, remuneration schemes should be able to dynamically adapt to the reductions in the costs of technologies. Similarly, in the opposite case of rising costs of RES generation, prompt adjustments may be necessary. Adjustments should only be applied to new investments, and not on a retroactive basis. Given the number of potential unexpected factors in the energy transition, a degree of flexibility will be necessary also in the future [80], p. 10. For these reasons, a flexible fine-tuning must be combined with a long-term deployment strategy stable enough to achieve long-term deployment targets [80].

3 Concluding Remarks

This chapter has discussed some usual claims about RES-E support using either theoretical arguments or empirical studies. It should be stressed that there is often an element of truth in those populate claims. The problem is that they miss the whole picture and they often have a simplistic perspective of complex problems, which limits the policy relevance of the analysis. Therefore, the replies are usually not an absolute rejection of popular statements (i.e., “claims”), which often contain an element of truth. They tend to complement these statements, integrating their insights.

Hopefully, the results of the analysis are useful for academic practitioners and policy makers alike. For the former, the discussion provides a research agenda on issues that are worth tackling in further research. For policy makers, we provide a balanced consideration of different arguments that should be taken into account when designing RES-E support schemes, both in Europe and elsewhere.

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The EU ETS as an Environmental Instrument

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Abstract After more than 8 years of operation of the world's biggest cap and trade scheme, Phase III of which has just been initiated, it is time to evaluate the performance of the EU ETS as an environmental tool. Now is the time to analyse whether it has been effective in inducing emissions reductions at a price marginally lower than other tools, such as carbon taxes or *command and control* regulation. This chapter analyses the decision that policymakers face in generating a strong price signal for carbon. It describes the trend over time in the carbon price in the EU ETS and relates its dynamics to a number of different factors. Moreover, it describes a set of specific elements linked to the EU ETS experience with a view to drawing lessons for the future.

1 Introduction

In the current times of financial uncertainty in which the very concept of monetary union as a key project of the European Union has been questioned, the strategy maintained by Europe in recent years in the fight against Climate Change is subject to lively debate. As Straw et al. [1] mention: "The EU's 'first mover' strategy on climate action has recently come under fire. Critics argue that by going it alone the EU is engaged in an act of futility, since it is responsible for only 12 % of global emissions. They say that this effort is piling costs on business, hammering competitiveness, and driving economic activity overseas (a process known as 'carbon leakage')."

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These criticisms have become louder in recent years as energy costs, and domestic debates about them, have increased.[1]

Through the so-called "20-20-20 Climate and Energy package" [11],[2] the EU made its commitment to work against Climate Change one of its four chief priorities in energy policy, the other three being energy supply security, economic competitiveness and the promotion of technology and employment.

As the mainstay of its strategy to combat climate change, the EU launched emissions trading (EU ETS, European Trading Scheme) in 2005.[3] The first period (2005–2008) of EU ETS could be considered as a trial of how a market based mechanism could be implemented in the EU. It covered around 12,000 facilities and emissions equivalent to almost 40 % of the EU total. The second phase (2008–2012) was extended to EU27 and Norway, Iceland and Liechtenstein and was designed to improve the system.

In Phase I of EU ETS (2005–2007),[4] European Union Allowance (EUA) prices started out at around €7 and surpassed €30 in 2006. This sharp rise was a consequence of uncertainties regarding the stringency of the cap and the shortage of allowances. These fears of scarcity were due to the power generation sector switching from gas to coal, pushed by rising gas prices. Only the power sector was trading in the EU ETS and it was assumed that there was a shortage in the market until the information on 2005 emissions was published. Since the data showed lower emissions than expected, and therefore a smaller expected deficit, EUA prices plummeted quickly to €10. As it became clear that the balance of the market would

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[1] However, the EUTS is not the only carbon market approach which is facing hard times. After the Warsaw Conference of Parties (COP) to boost international carbon markets there was little development. The final text on the pathway to a climate deal in Paris does not specify any role for markets. Developing nations were opposed to this. As Flynn [2] states: "(…) talks on a new market mechanism were discontinued. They will be reconvened next year in Lima, Peru. And discussions on a "framework for various approaches" (FVA)—the means by which carbon pricing systems worldwide could be linked—were also postponed (…)".

[2] The climate and energy package is a set of binding legislation which aims to ensure that the European Union meets its ambitious climate and energy targets for 2020. These targets, known as the "20-20-20" targets, set three key objectives for 2020: first, a 20 % reduction in EU greenhouse gas emissions from 1990 levels; second, raising the share of EU energy consumption produced from renewable resources to 20 %; and third, a 20 % improvement in energy efficiency in the EU [11].

[3] Two further Directives were enacted by 2009 to cater for the goals established in the climate and energy package: the Renewables Directive and the Fuels Quality Directive. A few years later, in 2012, another Directive was passed to deal with more issues related to energy efficiency. Although all these pieces of legislation deal in principle with different facets of the same problem and set different targets, the truth is that in practice they overlap various ways that affect the carbon price. For instance, the new Energy Efficiency Directive was passed with the praiseworthy objective of stimulating energy efficiency in diffuse sectors by promoting energy efficiency measures among end users, However the original draft, released in 2011, included power generation and refining, which were already covered by the EU ETS Directive, and caused a dramatic fall in carbon prices due to overlapping targets and the uncertainty created around the EU ETS Directive in the market [14].

[4] Phase I was a learning-by-doing period implemented by the European Commission "anxious to have a window of experience from which to learn and which would inform later stages of the trading scheme".

show a surplus, with no possibility of carrying over any allowance to the next period ("banking") the price fell to below €1 in 2007. EUAs stayed at that level for the rest of the period. Yet futures prices for Phase II remained at €15–20.

For Phase II the limitations found in Phase I were changed. The two key changes involved the process to build up the market cap: first, allocations to facilities were assessed by the European Commission rather than by Member States. Second, allocation was to be based on verified emissions in the previous period (2005–2007). Both measures sought to support the robustness of carbon prices. However all efforts to adjust the scheme failed due to the scale of the economic downturn just as Phase II entered its earliest stages.

During the first half of 2008, high energy prices (with crude oil peaking at $147/bbl. in July) sent EUA prices rocketing to €30. However the lack of industrial activity due to the economic downturn had a major impact on demand for EUAs. This effect made it unnecessary to buy EUAs to assure compliance. Therefore many carbon players saw the massive selling of EUAs as an easy way to generate revenues and improve their cash flow.

Prices dropped from more than €30 to €8 in just 5 months. However, although they rose to around €15/t in 2011, eventually the surplus built up was so important that the price collapsed to €5/t at the end of Phase II.

Across the next sections of this chapter the key features of the cap-and-trade systems will be reviewed. From the starting point of generating an external price signal for CO_2, carbon tax and carbon markets schemes are analysed detailing the pros and cons of both mechanisms. An Emissions Trading Scheme, and as such generating a price signal for carbon through establishing and stringent cap, was the choice of the EU regulators. European Scheme main design parameters like size of the cap, allocation methods and use of offsets are studied and the impact of demand drivers and market participant's assessed. Thus the revision of the EU ETS, from the very foundation of it across its key elements, all in the European economic and industrial environment of the past nine years, will lead us to the answer to the most important question. Is the EU ETS delivering the results it was design for?

2 Internalizing the Cost of Carbon

One of the main obstacles in the fight against Climate Change is the inability of the market to assign a value to the atmospheric assimilation of a greater amount of greenhouse gases (GHG). Industries and other GHG emitters do not feel the impact in their accounts of the inability of the atmosphere to assimilate emissions unlimitedly. This lack of a price signal means that there are no natural incentives in the balance of supply and demand for operators to reduce their emissions.

Lawmakers may use two main tools to solve this problem and create an artificial price signal: a carbon tax, or a CO_2 market. A carbon tax provides CO_2 emission reductions and provides clear information to emitters about the future cost of their emissions, but there is no such clarity as to the total amount of reductions that will be achieved. On the other hand, a carbon market gives clear information on total emissions into the atmosphere (“the cap”) but the price is unknown, since it will not be constant as it would be with a carbon tax but floating, depending on the supply and demand balance. In this case, the price signal needs to represent the marginal cost, i.e. the cost of the latest emission reduction made to meet the emission cap. This is the basic idea behind the EU ETS.

A carbon tax policy would mean that every facility[5] would have to pay a fixed price for each tonne of CO_2 emitted. Under this scheme the price of carbon is established and settled by the market regulator. As C2ES [4] mentions: “In principle, a carbon tax could be designed to produce the same overall level of emissions, distribution of emission reductions across sources and sectors, and aggregate costs as a cap-and-trade system. However, achieving this level could require adjusting the tax rate several times because of the uncertainty surrounding consumers’ response rates.”

On the other hand in a market based scenario each facility must surrender one emission allowance for every tonne of CO_2 emitted. The price of the allowances is settled by the market itself with no intervention by third parties. Therefore, in a market based mechanism the emitter could decide whether to increase its demand for allowances and go to the market to buy the marginal tonnes or reduce its demand of allowances and sell the surplus on the market. In this way the first emission reduction is always the one with the lowest abatement cost. This mechanism pursues not only environmental effectiveness but also economic efficiency. As Ellerman et al. [5] state: “These transactions produce a price per unit of pollution that provides the incentive to polluters to reduce emissions and sell the surplus to those who need to buy to cover their emissions. Emissions trading also provides signal to innovators to come up with new and better way to reduce emissions. Because those who can do so at least cost will reduce most, the overall burden on the economy of meeting the cap is likely to be achieved at close to minimum cost.”

According to economic theory both tools achieve the same results, with no externalities or uncertainties in either case. Therefore policy makers must decide whether they prefer predictability in the amount of the emission reduction (cap-and-trade system) or predictability in the price signal price of abatement (carbon tax). The EU decided to obtain a defined emission reduction target but with the risk of price volatility.

If the policymaker chooses a cap and trade scheme, then the first issue to be addressed is the cap of the market.[6, 7] A carbon market is an artificial market, so it depends on generating a shortage on a formerly free commodity (a tonne of carbon)

[5] The scope of this chapter does not include road transport. For further information on this issue see [3].

[6] This is not the only item that hinders the predictability and the behavior of the system. There are other two factors that cannot be predicted: the future and real costs of abatement and future energy prices and policies.

[7] This chapter considers the case of a cap and trade system where allowances are allocated for free through quotas of allowances issued to facilities as in the EU ETS example. There are other cases of cap and trade systems where allowances are not allocated for free [10].

in order to generate demand. Thus the mechanism for generating demand is influenced to some extent by regulatory perspectives. There is no scientific, technology based assessment for determining the stringency of the cap. Policymakers must find a balance between the degree of scarcity associated with the cap and the impact on the economic dynamics in the country/region where the market is deployed. A very ambitious policy on the reduction side will give rise to a lower overall cap on the carbon market. Thus the potential gap between projected emissions and the free allowances allocated will be wider and demand will increase, pushing up the carbon price.

On the other hand, if the market perceives that all the free allowances allocated are above the forecast figure for future emissions, the expected supply-demand balance will show a surplus, with a consequent drop in carbon prices.

Thus, a situation may arise where supply ("the cap") may be bigger than the demand that would have existed with no carbon market ("business as usual"). Such a situation would not provide a price signal because scarcity, a requirement of a cap and trade system, would not exist.

3 Building up a Robust Price Signal for Carbon

Hence the carbon price is critical to generate incentives for operators to take emission reduction actions and to make this environmental measure a successful one. At the beginning of the EU ETS, the prevailing consensus was that the legislator had just to set the cap for the total number of emissions to be allocated. Then the carbon price would arise automatically as an immediate indicator of the cost of reaching the environmental target. The main problem of the legislator, at that stage, was to avoid a pronounced increase in the carbon price that would make the cost of the reductions too onerous for companies, as this might potentially harm their competitiveness.

To prevent this scenario of high carbon prices, Phase II of the EU ETS introduced the possibility of using international offsets from Joint Implementation (the so-called Emission Reduction Units (ERUs)) and the Clean Development Mechanism (the so-called Certified Emission Reduction (CER) credits). This mechanism allowed EU ETS compliers to meet their liabilities in a cost efficient way.[8]

[8] "(…) Linking the Kyoto project-based mechanisms to the Community scheme, while safeguarding the latter's environmental integrity, gives the opportunity to use emission credits generated through project activities eligible pursuant to Articles 6 and 12 of the Kyoto Protocol in order to fulfill Member States' obligations in accordance with Article 12(3) of Directive 2003/87/EC. As a result, this will increase the diversity of low-cost compliance options within the Community scheme leading to a reduction of the overall costs of compliance with the Kyoto Protocol […] The plan shall specify the maximum amount of CERs and ERUs which may be used by operators in the Community scheme as a percentage of the allocation of the allowances to each installation. The percentage shall be consistent with the Member State's supplementary obligations under the Kyoto Protocol and decisions adopted pursuant to the UNFCCC or the Kyoto Protocol" [15].

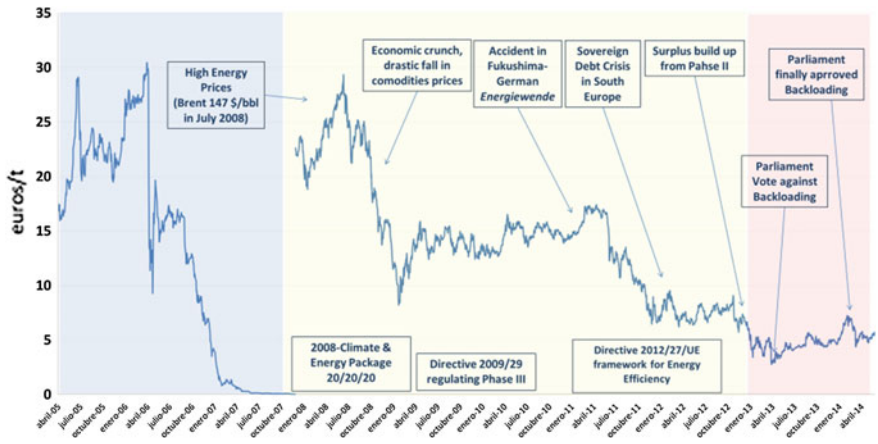

Fig. 1 Historical EUA front dec settlement price. *Source* own work based on Bloomberg data

However, the economic situation changed and economic activity slowed down[9] so that year by year an enormous surplus of allowances was created in the market. That resulted in a drastic fall in carbon prices and became a concern for legislators. Legislators seek a robust price signal as an incentive to reduce emissions. However, as policymakers do not have enough information on the marginal cost of CO_2 emission reduction in different sectors, at exceptionally low prices such as those prevailing in 2013 there is no guarantee that the carbon price is triggering any reduction actions or new investment.

In the case of the ETS, these basics play as in any other carbon market. However, there are a number of factors quite specific to this market during this period (2008–2013) which have played a key role in carbon price dynamics. Intrinsic and specific factors of this market have decisive impacts on price, with their own dynamics (Fig. 1).

Unilateral and single-country decisions about internal energy policies strongly affect how much CO_2 is emitted (CO_2 demand) but have no impact on the number of total allowances available on the market. This imbalance in demand and supply

[9] In the case of the EU ETS this issue has played a major role in the plummeting of carbon prices. Production grew between 2003 and 2007 by almost 3 % per annum, but decreased by nearly 2 % per annum from 2008 to 2012. Therefore, demand for allowances substantially decreased. As Egenhofer et al. [6] mention: "At the time of the hard-won compromise of the ETS review for post-2012, there was a general conviction that the new ETS would be 'future-proof', i.e. be able to cope with the temporary lack of a global climate change agreement and address competitiveness, yet able to drive decarbonisation of the EU economy. The 2008–2009 economic crises, however, has destroyed that confidence by a seemingly permanent dramatic lowering of EUA prices due to a rapid and dramatic decline in economic output. Ever since, EUA prices have been lingering below €5 per tonne of CO_2, going as low as around €2. Without political intervention, EUA prices are not expected to climb much higher throughout the period of up to 2020, largely because of the possibility to bank unused allowances between the second and third phase".

exposure has a decisive impact on prices, as can be seen clearly in the above graph, which charts the behaviour of carbon prices in the EU in the last few years.

An analysis of price trends in the EU ETS from 2005 to 2012 reveals that the main price drivers in Phase I were related to intrinsic elements (major differences between verified emissions and the cap, no possibility of banking between Phase I and II) while in Phase II extrinsic elements such as energy prices and economic performance had a stronger impact on prices.

4 Intrinsic Elements

The intrinsic factors of the EU ETS can be split into three groups: the number of allowances to be allocated, the method of allocation and the existence of an offsetting mechanism. All three are long-term factors, i.e. their impact takes more than one or two years to make itself felt.

4.1 The Size of the Cap

As extensively discussed elsewhere, this is the most obvious factor of any cap and trade system, since the "level of scarcity" (the balance between supply and demand) is the ultimate driver of abatement. However, this is a key factor not just for the EU ETS but for every carbon market. What makes this an EU ETS element is the reiterated failure over these eight years to build up a substantial deficit of allowances. A tighter cap would increase prices, incentivising more abatement actions to make total emissions meet the cap [12].

4.2 The Allocation Method

The decision to set the cap is independent of the decision of how to allocate allowances according to the cap. Allowances can be allocated for free or by auction. Free allowances can be assigned according to two criteria: grandfathering or benchmarking.

The EU ETS is not the first cap and trade system, but it is the first to incorporate facilities from completely different economic sectors, leading to different situations depending on transport costs, international competitiveness and whether or not the cost of carbon can be transferred to the end customer.

During phases I and II the behaviour of Member States in the EU ETS was very homogeneous, with almost all of the scarcity being allocated to the power sector, based on the idea that there was greater potential for cheaper and easier CO_2 reductions there than elsewhere. As Ellerman et al. [5] point out: "First, abatement was believed to be easier and cheaper for installations in the electric utility sector. Second, the electric power sector did not face any non-EU competition that would occasion leakage. Installations in the industrial sectors were seen to be competing in a world market, in which the prices were set outside the European Union, and the grant of free allowances was believed to be means of allowing them to avoid raising prices and thereby losing market share. In contrast, power stations competed in strictly European markets and would thereby be able to pass on their added CO_2 costs".

In a system based on free allocation, the depth of the market depends, among other factors, on the difference between that allocation and demand for emissions. Asymmetries between operators will cause some of them to have more allowances than others in certain circumstances, stimulating the market.

These asymmetries are generated primarily for three reasons:

- Non-equitable allocation. This is the case of several Member States, where more allowances are allocated to one sector than to others.
- Emission reductions caused by the fact that neither the legislator nor the operator can know the marginal costs of reduction in advance. In such cases, had the legislator taken this into account then windfall profits due to sales of allowances allocated in excess would have been avoided.
- Variability between production and emissions: different production situations may arise (plant shutdowns, maintenance, etc.) inducing variability in emissions.

The allocation system can either depend only on historical emissions (grandfathering) or take efficiency into account (benchmarking), but in either case demand will be caused by the difference between the number of allowances allocated for free and the need for emissions. This could cause distortions in the price signal. This effect is increased by the fact that many EU ETS operators are small facilities and are not active in the market. If allocation to such operators has caused them to have a surplus, that surplus may never reach the market.

However, the regulator has a simpler way of avoiding distortions from asymmetric allocation to different operators for these two systems: auctioning. This method helps the regulator correct inefficiencies in allocation, since all operators have to bid for the required allowances, making the price signal more reliable as it does not reflect differences between allocation and emission projection, but is based only on projected emissions. A full auction would not completely eradicate price distortions: there are still major changes in supply timing that can potentially cause temporary surpluses in the daily supply and demand market.

Applying auctions as the only allocation method would not be a wise policy without a global agreement against GHG emissions. Many operators which are regulated by a carbon market compete internationally: faced with international competitors who do not have to internalise the cost of their carbon emissions, they will be at a clear competitive disadvantage.

In Phase III the EU ETS has opted for a mixed method of allocation, with full auctioning for the power sector, where operators are not competing against facilities outside the EU (captive customers). What exactly does that mean? Power operators hedge their costs (related not just to CO_2 but also to raw materials) well before electricity is actually generated. So when they market electricity, depending on the current cost of CO_2 and raw materials and the market price of electricity itself, they decide which option is more profitable: producing and selling electricity or undoing their hedging positions and selling the raw materials and CO_2 back to the market. In this way they always get the opportunity cost of CO_2.

Other industries are unable to transfer CO_2 costs. EU companies that operate in, for instance the refining, chemical, metal and cement production industries have to compete with non EU producers that are not burdened by CO_2 emissions so they are unable to impose this extra cost under the threat of cheaper imports. For those industries which are unable to transfer their costs to their customers the EU ETS provides partial free allocations. These industries are also divided up according to the impact of carbon costs in their profits and losses and the intensity of trade in each sector ("sectors under carbon leakage risk" receive 100 % free allocations and other sectors receive less). The system for distributing free allocations is based on benchmarks, which are established generally on the basis of one product = one benchmark. So the calculation does not differentiate between facilities with different sizes, types of fuel or technologies. A product benchmark reflects the greenhouse gas emission performance of the top 10 % of best producing facilities in the EU for that product. So every facility in the EU that produces that specific product would receive free allowances equivalent to the emissions of the top 10 % best performing facilities. Every tonne of CO_2 above that 10 % level must be acquired on the market by industrial operators to fulfil their requirements.[10]

4.3 Offsets

One of the structural factors of the EU ETS is the ability of operators to import different credits (offsets) at comparatively lower costs than EUAs. These international credits, CERs and ERUs, are not assigned by the EU or auctioned; they are issued by the United Nations under the Kyoto Protocol (CERs from the Clean Development Mechanism and ERUs from Joint Implementation), and were originally intended to help developed countries meet their Kyoto targets by providing flexibility to emissions trading.

[10] "(…) According to the European Commission (2012), some additional 500 million allowances from three exceptional sources have been brought to the market in 2012/2013: (1) Unused allowances from the second phase national new entrants reserves were auctioned at the end of the second phase. (2) The European Investment Bank is selling a fixed amount of third-phase allowances in order to fund a number of carbon capture and storage and innovative renewables projects (NER300 program) (3) Some third-phase allowances have been auctioned early in order to avoid the scarcity that was feared at the time the climate Package was negotiated in 2008/2009. As emission allowances not used in the second trading period (2008–12) can also be held over and used in the third trading period, a surplus of "well over 1.5 billion allowances, and even as large as 2 billion allowances" might have accumulated at the start of the third phase" [13].

The EU ETS has also agreed to surrender these credits up to a certain threshold, based on a percentage of either emissions or free allocation. Both CERs and ERUs are traded in the secondary market, as are the EUAs (emission allowances in the EU ETS), and there are also derivatives, options, swaps, etc., with CERs and ERUs as underlying assets, but their price mechanisms are different.

The main differences between EUAs and international credits as compliance instruments in the EU ETS are:

- Liquidity: much lower for international credits than for EUAs.
- Homogeneity: there are no qualitative differences between EUAs; however, international credits are perceived as more or less valuable according to their technology, country of origin, date of issuance, etc.
- Regulatory risk: although international credits are valid for compliance, they are subject to certain restrictions by the regulator. For instance CERs from HFC destruction projects and ERUs from countries without binding targets under the Kyoto Protocol's Second Commitment Period will not be valid in the Phase III of EU ETS.[11]

The prices of international credits have fallen dramatically since 2011 due to the lack of international demand for them, causing a huge imbalance. The acceptance of international carbon credits in the EU ETS is established as a mechanism to reduce the upside price risk and to provide flexibility to the system. However the massive use of international credits could be detrimental to the emission reduction goals of the EU ETS. A wide price gap between EUAs and international offset could dramatically increase that risk and boost the use of low-cost international credits thus reducing the incentive for companies to invest in emission reduction technologies in the EU ETS. For this reason the regulator introduced the aforementioned offset usage threshold.

The use of international credits has been the subject of controversy due to the decision of the European Commission to ban the use of credits from certain types of project (HFC-23 credits) in the EU ETS as from April 2013. This prohibition of credits that were already in the accounts of EU ETS participants led to major legal uncertainty in the system concerning the use of international credits during Phase III, considering that the Commission might make similar decisions regarding projects of other types (Figs. 2 and 3) [13].

[11] Several quantitative and qualitative restrictions apply to the use of ERUs and CERs. Credits from GHG emission reduction projects registered before December 31, 2012 can be used from all countries, except projects from: (i) Land-Use, Land-Use Change, and Forestry (LULUCF) projects; (ii) Nuclear projects; (iii) Large hydropower projects not in compliance with the World Commission on Dams guidelines; (iv) HFC-23 destruction projects (as from May 1, 2013); (v) N_2O destruction projects from adipic acid production (as from May 1, 2013).

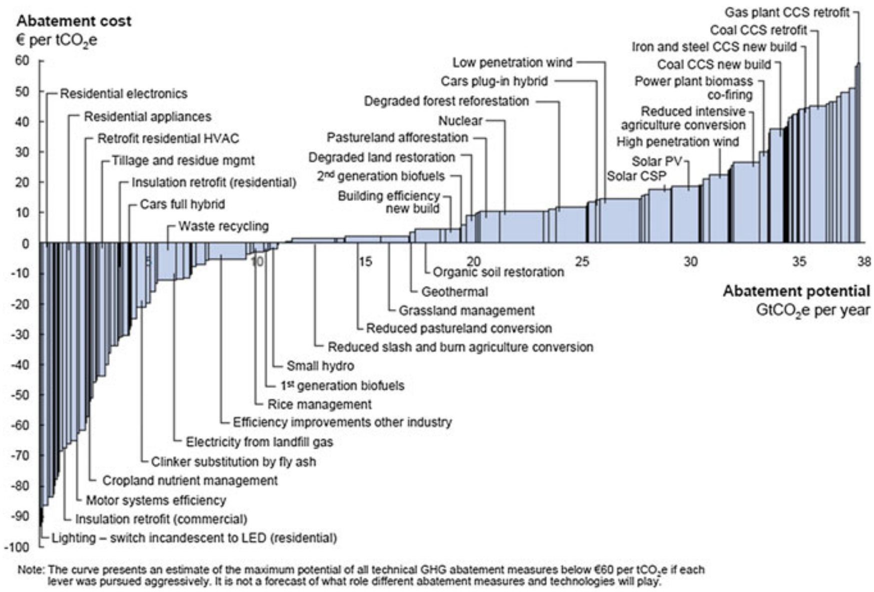

Fig. 2 Global GHG abatement cost curve beyond BAU 2030. *Source* Mckinsey and Company [7]

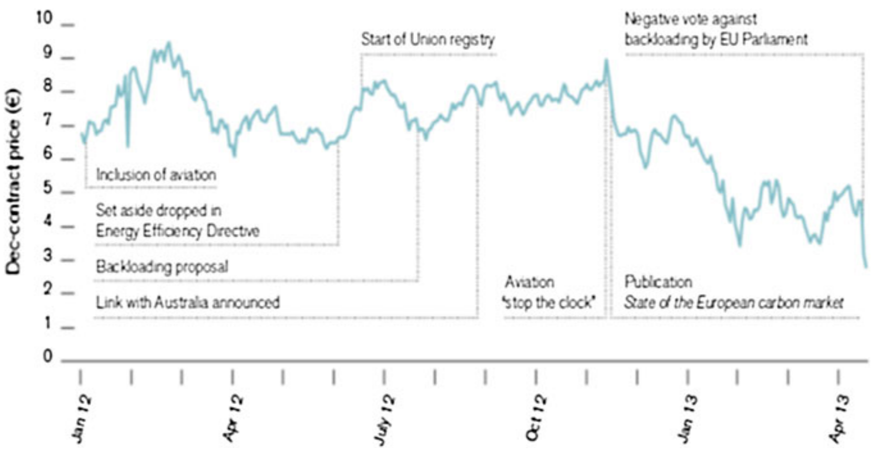

Fig. 3 Carbon price trend labelled with key developments in the EU ETS in 2012. Source of carbon price (EUA price for December delivery contracts): Thomson Reuters point carbon, April 14, 2013

5 Extrinsic Elements

5.1 Dark/Spark Spread

One of the main drivers in the carbon market is the spread between the generation of power with coal or with gas, commonly known in the market as the "dark spread" and the "spark spread" respectively. If spreads include the cost of CO_2, they are referred to as the clean dark/spark spread.

A look at the behaviour of this spread reveals that when the price of carbon decreases the spread increases, i.e. there is an inverse relationship. This is because producing with coal is cheaper than with gas, but it is more polluting, thus increasing production costs since more emission allowances are needed (Fig. 4).

5.2 Weather

With power utilities being the main sector in the EU ETS, the weather is a key factor affecting emissions and thus driving EUA prices. Extreme conditions affect the demand for allowances. Cold winters increase the consumption of coal and gas for heating, while hot summers increase power consumption for air conditioning. The wind and the sun can also change the power mix through renewable energy, increasing or decreasing demand for allowances.

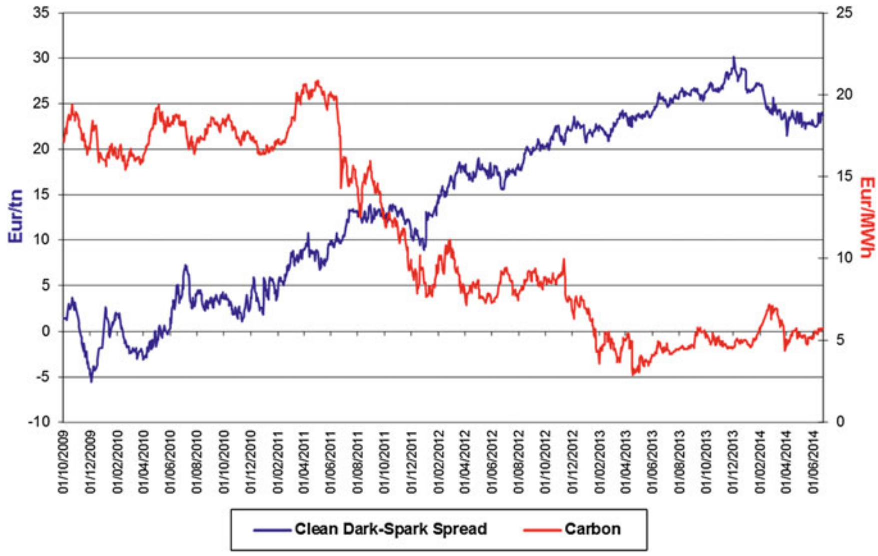

Fig. 4 Carbon price versus clean dark/spark spreads. *Source* own work based on Bloomberg data

As Ellerman et al. [5] point out: "(…) Unseasonable temperatures have had an effect on first-period EUA pricing. During the winter of 2005/6 lower than average temperatures increased energy demand and had a positive impact on EUA prices, as did in higher than average temperatures during the winter of 2006/2007 resulted in a lower energy demand than anticipated and contributed to the fall in the first period price that was occurring at this time".

5.3 Market Participants

There are three main groups of participants in the EU ETS, grouped according to their interests and characteristics: financial intermediaries, power utilities and other operators.

The Financial Intermediaries' group includes all companies that trade on the emissions market but have no compliance obligations under the EU ETS. This includes banks acting as market-makers providing liquidity to the market, brokers acting as intermediaries in OTC transactions, investment funds, speculators etc. Mainly during the second phase of the EU ETS, many banks and financial institutions were attracted by the emerging carbon market. However the collapse in carbon prices and the instability in carbon policies in the EU have produced the opposite effect, since it is now less widely perceived as profitable.[12]

Power utilities are very active in their carbon markets, since they usually hedge the emissions from their future power sales, buying allowances on spot or futures markets. In Phase II they receive no free allocations, as they transfer the full cost of carbon to their customers.

The "other operators" category includes the rest of the compliance operators: oil and gas, paper, cement and metal industries, airlines etc.

Their main concern is the potential loss of competitiveness with international rivals which are not affected by the cost of their carbon emissions, as they are not able to fully transfer their cost as they compete in globalised markets.

6 Main Conclusion

Almost 9 years have gone by since the launching of the EU ETS system as the corner stone mechanism to achieve European Climate Change goals safeguarding Energy Policies simultaneously.

[12] According to a former head of carbon and coal at Barclays Plc, around half of the 30 brokers that were present in the market have already left it or at least reduce their desks in the last 5 years. In 2013 brokers share of the market was 10 %, all-time low and down from the 30 % registered in 2012, according to CME Group Inc.

From this relative long term perspective, this chapter has reviewed the key design features of any cap-and-trade scheme, and specifically the EU ETS characteristics.

Internalizing the carbon cost through an external price signal, and providing a strong and scarce message to the market have revealed as the main important factor for the success of the system [8].

EU ETS started with the uncertainty of the verified level of emissions and the first phase (2005–2008) was strongly affected by an insufficient level of scarcity and thus the prices were depressed. During second phase (2008–2012), the cap was set based on historical verified emissions and the price signal was powerful during the first months. But the world economic crunch impacted the level of industrial activity in Europe dramatically. Once again the system found itself in an excess of allowances scenario, a very important surplus started to build up and the prices plummeted again. The Phase III started in 2013, strongly affected by the surplus in the market and with new rules trying to reinforce the long term signal. However so far the credibility of the system is still at stake and EU ETS operators do not feel the urge to reduce their emission since they feel comfortable with their excess positions, even in the long run.

So it is fair to say, analysing what has happened, that EU ETS has worked properly in a technical way. The market price for CO_2 has been the answer to the supply and demand balance, experiencing high prices during the few moments when the market feel that the allowances were scarce and low prices when the market participants sense the excess of allowances and therefore the urge to reduce emissions.

However the system has failed providing the needed level of scarcity to produce the price signal that boosts clean technologies and emissions reduction. Some can argue that the 21 % emissions reductions in 2020 compare with 2005 goal for the EU ETS sectors will be fulfil, but the reasons that triggered the reduction are not those intended by the regulator and the price has not justified the investment on low carbon technologies [9, 12].

There are several reasons to explain why the level of scarcity has been inappropriate; uncertainties on the verified emissions of EU ETS sectors during the first years, low industrial activity due to the economic crisis which has resulted in low demand both for final goods and electricity, overlapping effects with other European policies like Renewable Energy and Energy Efficiency Directives, excessive usage of international credits in an already oversupply market, inefficiencies related to the distribution of free allowances to prevent carbon leakage.

But beyond all these side effects underlines the true fact that the supply, or cap, is not resilient to socks or significant changes in demand. The cap is set by the regulator following a path to achieve the emissions reductions desire, and not taking into account the capacity or the effort needed by the operators to produce this reduction. Therefore the level of ambition has significant different implications if allowance demand is healthy and installations would prefer emissions reductions at a lower cost than buying them in the market, or on the contrary in a situation with poor demand where the structural need of reducing emissions is low even with a reducing cap.

So it can be concluded that the EU ETS has not delivered exactly the results intended when it was implemented. It has produced emissions reduction but is not clear if these reductions have been achieved at the least cost, and for sure it has not promoted low cost technologies to assure Climate goals in the long term. That does not mean that the work done is not valuable. The experience and knowledge build during these years will be a key for reforming the system which is valid technically and with de convenient reform, specially linking the level of ambition with the demand situation, will deliver the European Union climate goals to 2030 and eventually to 2050.

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Renewable Energy and Transmission Networks

Luis Olmos, Michel Rivier and Ignacio Pérez-Arriaga

Abstract Achieving the integration of large amounts of Renewable Energy will certainly impact the development and operation of the transmission network. Making efficient use of Renewable Energy primary resources within a large region will require the transportation over long distances of large amounts of energy and will lead to less predictability and more stress in the use of the transmission network to cope with the intermittency and variability of such generation resources. This chapter identifies and discusses the main impacts related to the existence of renewable generation on those aspects of the functioning of the system that are related to the transmission grid. Expansion planning may probably need to take place in an integrated manner at regional level; while long-term transmission rights will need to be somehow accounted for in the planning process; these rights will have to be made available to Renewable Energy based generation; changes in electricity transmission technology may be necessary; markets will probably need to move closer to real time to better address imbalances caused by Renewable Energy generation; and the number of connection requests will probably increase, at least in those areas with abundant renewable primary resources; these resources may need to be provided priority access to the grid; finally, due to the inability to appropriately predict network use, transmission tariffs computed ex-ante will be less efficient, since they will be less likely to reflect future system conditions; on the other hand, updating network charges periodically defeats their main purpose of sending credible locational signals to prospective investors.

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1 Main Features of Renewable-Based Generation Affecting the Transmission Activity

Generation based on Renewable Energy Sources (RES generation) must be integrated massively in our power systems in order to achieve energy and environmental policy objectives currently being set all over the world, [13]. But distinct features of RES generation, namely the intermittency of its power output, its cost structure, and the uneven geographical distribution of RES generation primary resources, are expected to have a significant effect on the economic and technical conditions applying in those power systems that exhibit large RES generation penetration levels.

Power production from RES generation is, for most of these technologies, to a large extent unpredictable—except in the very short term—and largely variable. This results from the fact that the output of these units largely matches the amount of renewable primary energy available at each time, wind and solar, typically. The latter may exhibit large, unexpected variations over relatively short periods of time. In order to keep the balance of power in the system, the operation of the rest of generation and the demand, and to some extent even that of transmission and distribution, needs to adapt to the availability of the RES resource.

Apart from this, the structure of costs of RES generation also differs from the thermal one, which traditionally has largely determined power prices in most systems. Thus, conventional generation is characterized by lower ratios of investment costs to variable production ones than RES-based generation. As a consequence of this, when large RES generation penetration levels are achieved, market prices reflecting short-term marginal costs will significantly decrease with respect to current levels over long periods of time (when the amount of RES-based generation that is available to produce is significant), while prices at times when most of RES generation is not available will be very high, i.e. large price spikes will occur. This may ask for a reconsideration of present market pricing rules and transmission regulation. Regarding transmission, mechanisms to provide long-term access to the use of the grid will probably be needed to facilitate the installation of far away RES generation.

Lastly, contrary to what happens with fossil fuels burned by conventional generation capacity, a large fraction of primary renewable energy resources, like wind, solar radiation, or even water in the amounts needed for power production, cannot be transported to other places in the system than those where they are naturally present. Then, cost effective power production from RES in large amounts must take place where the resources are located. This implies that the geographical distribution of RES generation will not match largely that of demand, resulting in large power flows covering large distances. Making efficient use of RES primary resources within a large region will require the transportation over long distances of large amounts of energy and will lead to less predictability and more stress in the use of the transmission network to cope with the intermittency and variability of such generation resources. This may require, as explained later, to resort to the use of higher voltage levels or high voltage direct current (HVDC) technology, leading to changes in the way most transmission networks are currently structured and operated.

RES-based generation requires the support of conventional generation when there is a lack of wind or solar radiation. The more geographically dispersed these RES resources are, the less probable it is to face a simultaneous lack of production from these resources. The wind will probably blow in some parts of the region and the sun will shine in other zones of the region. But this geographically-changing mutual support will require the existence of enough transmission capacity to cope with all these resulting flows. Moreover, whenever conventional generation support is needed to cope with extreme adverse conditions (i.e., a generalized absence of primary RES resources), the existence of a well developed and meshed network will permit sharing these back-up generation units among the entire region.

All these features of RES generation will significantly affect the way transmission networks are developed and operated, and therefore how the transmission activity is regulated and managed [16]. The rest of the chapter is as follows. Section 2 discusses the effect that the existence of RES generation has on the planning of the expansion of the grid. Section 3 focuses on how access to the transmission grid must be regulated and managed in the new context. Section 4 describes some impacts the existence of RES generation may have on the allocation of transmission costs. Finally, Sect. 5 provides the main conclusions drawn from our analysis.

2 Planning the Expansion of the Grid

As a result of the deployment of large amounts of RES generation, expansion planning may probably need to take place in an integrated manner at regional level due to the resulting increase in power flows between areas with abundant economically efficient RES resources and those that are lacking them [22]. At the same time, mechanisms to manage in the long term the access of RES-based generation, and probably also part of conventional one, to the transmission grid will become necessary. What is more, demand for long-term transmission capacity products will probably condition the optimal development of the grid. The format of these rights will have to be defined and even the mechanisms for coordination between transmission and generation development will have to be revisited.

Lastly, and related to previous arguments, transmission expansion planning algorithms will probably need to be upgraded to be able to deal with much larger systems than those considered in traditional expansion planning exercises, while considering a much larger set of operation situations as relevant for the dimensioning of the grid.

2.1 Institutional Setting Adapted to the Integration of RES Generation in Several Areas of a Region

Installing and operating the most efficient RES generation that may possibly exist in a vast region requires building a significant amount of transmission capacity to be used by power exchanges among areas in this region. This, in turn, requires planning and managing centrally, in a closely integrated way, the expansion of the grid, since the benefits produced by many of the required network reinforcements are not perceived by local network users but by those located in far away parts of the regional system. In other words, the entities in charge of identifying and approving the required network investment projects must jointly consider the benefits (both positive and negative) perceived by all agents in the region. This significantly conditions the nature of entities leading the expansion of the network. But besides this, the responsibilities and interplay between parties throughout this process will need to be reconsidered as well.

Previous publications on the institutional setting of the development of the network, see [20, 25], point out that, due to the lumpiness of network investments and the economies of scale characterizing these investments, congestion rents corresponding to most required new lines do not suffice to pay their cost. If left entirely to the private initiative, the congestion rents of any new line would be maximized for a size of this investment well below the socially optimal one. Then, in general, private merchant promoters cannot be trusted to build all necessary reinforcements. Moreover, since the benefits associated with any investment are frequently perceived by a multiplicity of network users, establishing a consortium of beneficiaries interested in promoting and paying future lines is a very difficult task.

In a context dominated by conventional generation, most local systems existing in a region (each one controlled by a single Transmission System Operator, TSO) have more than enough generation capacity to supply their load. Thus, even when there may be economic reasons for large power exchanges to take place among these systems, the former have traditionally been very modest. Consequently, planning the expansion of the grid could, for its most part, take place separately within each system. However, when power produced by RES generation located predominantly in some systems must be used to supply load in others, transmission reinforcements needed to host the corresponding flows will benefit several of them. This may require the existence of regional institutions to identify, promote and approve these reinforcements, or an unusually strong level of inter-system coordination in decision-making. Therefore, for their most part, new transmission assets of regional significance have to be built as regulated investments, being part of a regional network expansion plan centrally designed and approved.

This involves that, instead of having a regional expansion plan that results from adding up investment projects identified and approved separately by each SO and local planning authority with jurisdiction over each area within the region, there is a need for a unique SO, or regional network expansion planning entity, to compute the expansion plan in the first place, and a single authority to finally approve each of the projects that are part of the plan. Note that the need to centrally manage the expansion of the grid is not only motivated by the existence of high RES penetration levels. Centrally planning the expansion of the grid and operating the regional system and market afterward would result in a significant increase in economic efficiency, even in regions where the contribution of RES generation to electricity supply is marginal. However, in those systems where a large fraction, or even the majority, of total generation is based on RES, centrally computing the expansion of the grid is critical to securing the electricity supply, i.e. to achieving a safe and reliable operation of the system.

Not all regional electricity markets expected to host a significant amount of RES generation shortly have managed to comply with this requirement. Thus, whereas the expansion of the grid used by regional transactions in Central America is planned by the regional System Operator, EOR, and the undertaking of each of the projects comprising the plan, as well as those proposed by private promoters, is to be approved or rejected by the regional regulator, CRIE, the Internal Electricity Market (IEM) of the European Union and the set of regional markets developing in the US have not got, up to now, to the same level of integration of the planning of the expansion of their grids. Within the IEM, however, several steps have been already undertaken towards a more coordinated approach, which may lead in a close future to a centralized regional transmission network planning. Currently, the European association of electricity TSOs, ENTSO-e, together with the Agency for the Cooperation of Energy Regulators, ACER, must periodically produce a pan-European network expansion plan. However, this expansion plan is only indicative. Therefore, national authorities within each country may decide not to implement part of the network reinforcements included in the centralized plan, see [9]. In the US, two levels of regional network expansion planning coordination should be distinguished. Regions comprising several systems have been defined, within which a common regional expansion planning of the transmission network is carried out. Even more, within some of those regions a Regional Transmission Operator (RTO) is in charge of the coordination of both the market and the system operation. On the contrary, coordination among these regions (interregional coordination) is still very loose. The Federal Energy Regulatory Commission (FERC) Order 1000, see [10], mandates each region (Independent System Operators or Regional Transmission Operators) to develop its own transmission expansion plan and to coordinate bilaterally with its neighbors. FERC Order 1000 also asks system planning authorities to look for interregional network reinforcements that may be more cost efficient than those computed separately within each region. However, this does not guarantee that systematic coordination will take place among network expansion proposals in neighboring regions.

The need to build large amounts of transmission capacity in order to allow large flows to take place over long distances involves being able to raise a significant amount of funds. This should condition the nature of entities in charge of building the transmission system and the regulation governing the development and operation of the transmission network. Owners of the grid, i.e. those raising the required funds and constructing new transmission assets, should have large financing capabilities. At the same time, the regulation in place should provide assurance to potential network investors that they will be able to recover the cost of the investments and will make reasonable profits out of them.

As previous research publications on the financing of large infrastructure projects in multinational environments have pointed out, see for instance Newbery et al. [17], targeted financial support from funding entities focused on regional cooperation should address projects of regional significance affecting a large number of systems in the region and/or featuring innovative technologies that are, therefore, not fully mature yet and might not be part of a formal regional plan. Regional cooperation funds are limited by their nature. Therefore they should be spent carefully to encourage the construction of meaningful projects that have financing difficulties, perhaps because of a lack of agreement about the allocation of the cost of the project among the affected systems. These funds could be addressed to close any financial gap that may exist to recover the total costs of the project.

It is of essence that the regulation governing the development, and the cost allocation and recovery of the regional grid should provide certainty to potential investors that they will be able to make reasonable returns on their investments. This requires having regulation that is as stable as possible but, at the same time, results in an allocation of the cost of reinforcements to the several systems in the region that they perceive as fair, so that none of them opposes the construction of the assets involved, see [2]. This will be discussed in Sect. 4 of this chapter.

2.2 Integration of Long-Term Transmission Contracts in Expansion Planning

In a context with very high penetration levels of RES, market prices over long periods of time will be very low, while during those periods when RES generation is not available, prices will be much higher. Then, revenues of generators participating in short-term energy markets will be very volatile and, to some extent, unpredictable in the short term. This should not be a problem for the investors, as far as the predicted income from market prices in the medium- and long-term results in an adequate level of remuneration. However, it may be perceived as a relevant risk by financing institutions, which could make access to funds to support these projects significantly more expensive. A more serious problem is the impact of regulatory uncertainty, since at least for the time being, the level of penetration of renewables directly depends on regulatory decisions. This motivates that both conventional and RES generation will need to hedge their revenues against these uncertainties. Otherwise, lack of confidence about future revenues might probably deter potential investors from undertaking the construction of all types of generation whose revenues are not sufficiently guaranteed by regulation.

Generation capacity mechanisms could be implemented to allow potential investors to have more certainty over their revenues. Several mechanisms to achieve this exist, from capacity markets to bilateral contracts signed between the

SO and new generation owners. Specific methods—such as feed-in-tariffs or green certificates—can be used to encourage investment in RES generation. However, this alone will not suffice to provide a shield against volatility in revenues to RES-based generation located in far away areas that are not strongly connected to the rest of the system, where most of its power output will be consumed. Ensuring the ability of these generators to be profitable requires providing them with guaranteed access to the transmission capacity needed to transport their power output from where they are located to major load centers. This calls for the deployment of transmission capacity mechanisms where these generators can buy well ahead of time the right to use the transmission capacity they may need.

However, issuing rights over transmission capacity may condition the future needs of this capacity. Transmission rights issued in the long term may have an impact in the operation time frame, whether with physical rights, and therefore their owners have the right to physically access the grid, or with financial rights, and therefore congestion rents accrue to the right holders. However, given the long-term nature of transmission right auctions, much of the capacity allocated to agents through long-term contracts may not have been built at the time these agents buy it. Hence, demand for long-term transmission contracts must be considered jointly with best estimates of the future location and operation profile of other generation and load to compute the optimal development of the grid.

The features of transmission rights may condition the need for transmission capacity. Thus, transmission capacity to be built will be smaller if rights are defined as obligations to use the transmission capacity they refer to instead of options, which would entail the right owners to use this capacity, or earn the corresponding congestion rents, only if this suits them. If rights are defined as options, there will be more uncertainty about the eventual use that right holders will make of the transmission grid, or the congestion rents they will be entitled to. Other features of transmission rights may also impact the construction of transmission capacity, like, for example, whether rights refer to the capacity needed to inject power at a certain point of the system and withdraw it at another one, i.e. whether they are defined as point-to-point rights, or instead they refer to the capacity of specific predefined bottlenecks to be reinforced. A review of different possible formats of congestion rights, and their impact on the efficiency of the system, can be found in [1, 20, 23].

The need to allocate transmission contracts to part of new RES generators and conventional ones in the long term, and the impact that the allocation of rights will have on the profitability of the generation projects themselves and the need of new transmission capacity, advices not to decide separately on the development of this generation and the grid, but instead to call joint generation and transmission capacity auctions. In these auctions, agents would submit bids on the prize at the connection node that they would like to sell their output at. Then, the central system planner would determine, taking into account the prize they would be paying for this electricity and his best estimates of the output profile of this generators under existing system conditions, which of these bids to accept.

This issue has been discussed, among others, in studies analyzing the integration of Europe with other peripheral regions, where RES-based primary energy sources may be more abundant and economical than in the IEM, like the North sea to the North of Europe, or Northern-Africa to the south of Europe, see [5, 7].

Some of the latter issues will be discussed when reflecting on the allocation of transmission rights in the long term.

2.3 Upgraded Algorithms for Network Expansion Planning

Given the intermittent nature of the output of most RES generation and the non-homogeneous distribution of primary renewable energy resources, the deployment of large amounts of this generation is expected to result in a significant increase in the size and diversity of power flows among areas in a region comprising several systems. These directly result from the rise in the variability of system conditions over the entire region. This will increase the number of operating conditions to be considered in whatever planning procedure that is adopted.

If very large amounts of power have to be transported from distant places—offshore wind production from the North Sea, solar power from Northern Africa to Europe, large wind resources from the sparsely populated Midwest in the USA—and very broad market integration is an objective, then just reinforcements of the existing high-voltage grid (400 and 220 kV in Europe) may not be sufficient and some sort of overlay or super-grid may have to be built, perhaps using higher voltage levels and direct current (DC) technology. As a consequence of this, a large number of technology options will have to be considered in the planning process, ranging from small but numerous incremental AC reinforcements to the existing grid, to large HVDC corridors that may or may not be part of a regional super-grid, including higher-than-conventional-voltage AC lines.

The development of the network for all the systems in a region will probably have to be planned in an integrated way, since benefits from the required reinforcements will not accrue to a single area or system but to several of them. Lastly, due to the fact that the size of reinforcements to undertake in the long term future is huge, network investments already undertaken in the short-to-medium term should be consistent with long-term objectives, and therefore represent an intermediate step towards the achievement of the integration of very large amounts of RES-based generation (almost completely replacing conventional one on a daily basis).

In this new context, computing the optimal expansion of the transmission network in a region ideally requires making use of highly efficient computer tools, able to automatically produce a coherent ensemble of network reinforcements in several time horizons that are consistent among them and can be deemed robust against the multiplicity of scenarios that may unfold in the long-term future. The expansion planning tools must be dynamic, meaning that a sequence of coherent sets of reinforcements to be deployed in different time horizons, instead of just for a single target year, must be computed. The model must be also stochastic, so that it may consider several stochastic parameters that can influence the optimal transmission expansion decisions: amount and type of RES available in the future, electricity demand levels, the level of hydro inflows, and fossil and renewable fuel costs.

Models must also be multi-criteria, meaning that some of the main quantifiable objectives to be achieved as a result of the reinforcement of the grid will have to be somehow incorporated into the expansion problem objective function. Main system variables to be optimized shall relate to the reliability of system operation, transmission network losses, conventional and RES-based generation CO2 and other pollutant gas emissions, the environmental (visual and other) impact of the transmission grid itself, and transmission grid investment and variable operation (power production) costs.

Given the long lead times considered in the planning problem, the model will typically consider only the so-called DC approximation to the load flow equations, assuming that voltage and reactive support problems can be addressed in shorter-term grid expansion planning analyses as well as in the operation time frame. However, the decision on which level of detail to adopt for the representation of the flow of power in the network is to be made in the light of the size and technical characteristics of the problem to be solved.

Expansion planning algorithms may be based on a functional decomposition between a first module aimed at the automatic generation of network expansion plans, using optimization techniques or meta-heuristics ones, and a second module that evaluates each plan and computes its cost and reliability metrics. For a review of some of the most relevant publications on transmission expansion planning see [14].

There are several projects funded by the European Commission to study the transmission planning of the European grid from several perspectives: Realisegrid, SUSPLAN or E-highway2050. Feasibility studies on the integration of the North of Africa and European electricity systems have been launched by the Dii and Med-grid consortiums, see [6, 8, 15, 24, 26].

3 Access to the Transmission Grid

Long-term transmission rights will have to be made available to both RES-based and conventional generation. Research is needed on how the availability and format of these rights will affect transmission capacity allocation algorithms.

In order for markets to allow RES generators to better address imbalances caused by the intermittency of their output, short time markets will probably need to move closer to real time. This fact, together with the increase in demand for long-term transmission capacity products will certainly condition the schemes for allocation of available transmission capacity in the different time frames when it is offered.

Regarding the regulation of connection to the grid, the number of connection requests will probably increase, at least in those areas with abundant renewable primary resources. At the same time, RES generation will probably be provided priority access to the grid. Mechanisms to deal with very large numbers of requests to connect to the grid, some of which will not materialize, and to make compatible priority connection for some generators with the efficient development of the system will have to be put in place.

3.1 Long-Term Transmission Capacity Allocation Process; Format of Long-Term Rights

Defining long-term transmission contracts and the process of allocation of transmission capacity will involve specifying the format of auctions and that of products exchanged. As already mentioned, long term transmission capacity products could be combined with energy long-term contracts at the point of delivery to define energy contracts at the point of connection of new generation. This would involve merging long-term generation and transmission capacity auctions, which would involve, for a start, leaving both processes in the hands of the same entity. Alternatively, transmission contracts can be sold separately from energy ones. But in this case, there is a risk that the allocation is inefficient in the sense that new generators may buy different amounts of transmission and energy contracts, which would provide them with under or over protection of their energy supply from the risk associated with the volatility in the value of transmission capacity.

If transmission products over still-to-be-built capacity are defined and assigned in the long term, then the central auctioneer should make sure that there is enough transmission capacity for the most efficient power injections and withdrawals while, at the same time, checking that the transmission rights that are issued can be guaranteed (or that there will be enough funds to pay back congestion rents corresponding to these transmission rights). This revenue adequacy criterion should hold when considering jointly the transmission grid that exists and the new one. In other words, power transactions backed by those long-term transmission contracts that are issued should be simultaneously feasible with power injections and withdrawals that, despite not being backed by long-term transmission contracts, would allow the system to achieve energy policy objectives (safe supply of expected load that is sustainable in time from a socio-environmental point of view) at the lowest possible cost. The specific formulation of the long-term capacity allocation problem, namely that of the objective function to consider and the whole set of constraints to enforce, is still to be defined.

In the medium term, transmission contracts should still be sold to agents, though these contracts should refer to already existing capacity, since there would not be enough time for new transmission capacity to be built before delivery time (real time). Assuming transmission contracts sold do not interfere with the efficient use to be made of the grid in real time, given that no new transmission capacity is to be built as a result of medium-term auctions, one shall conclude that these auctions should not impact the short-term energy dispatch. Hence, the optimal energy dispatch would not need to be computed at the same time that medium-term transmission contracts are sold. That is to say, stand-alone transmission capacity auctions would take place. Transmission capacity auctions have long been investigated. Therefore, their format is well known. Still, contracts of different types may be auctioned. As explained in the next section, whereas in the long-term (generation and) transmission capacity auctions the whole existing amount of capacity in the time horizon concerned should be considered, the amount of transmission capacity to be made available in each of these medium-term auctions should be thought carefully.

The eventual use to be made of the grid by long-term transmission contracts, or congestions rents to be earned by their owners, will of course depend on the format of these transmission contracts. Transmission contracts should, in the first place, provide a valuable hedge to potential buyers. This means that, in the long term, they should be flexible products allowing their owners to shield against the uncertainty not only concerning the conditions applying in the system, but also the uncertainty concerning what the output of these generators will be at each time of the year. Then, options should be appreciated by agents in the long term. In the medium term, uncertainty may be lower regarding the overall system development, and the available output of conventional generators, but not so much regarding the specific conditions affecting the amount of primary RES energy available, and hence the level of available production capacity of these generators at each time. Then, conventional generators could be more inclined to acquire obligations, while those to be bought by RES generators could still be options. Only in the short term will RES generators have some certainty about the conditions that they will face. In any case, both options and obligations should be made available to agents willing to buy transmission contracts in the medium and long term.

Probably, agents will be most interested in buying point-to-point contracts, since they provide the former with a full hedge against the variability of the price of accessing the transmission grid, see [23]. Only if the set of transmission bottlenecks that may exist is rather small, it could make sense for agents to separately buy rights over the capacity of those bottlenecks they wish to use. In the latter case, buying flow-gate contracts that they can easily trade in bilateral markets could be interesting. For a discussion of the use of point-to-point and flow-gate rights, see [12, 20, 21]. As for the financial versus physical nature of rights, both could be an option, and the first should not condition the physical energy dispatch. However, only if agents acquire physical rights, they may be entitled to earn firm generation capacity payments, see, for a example, [3, 4] to learn about the regulation of firm transmission contracts in the Central-American market. The possibility to have access to signing firm supply contracts could lead agents to acquire physical transmission contracts, especially those generators whose capacity can be considered firm (no intermittent ones). Much has been published on the analysis of the pros and cons of trading both types of products, see Batlle et al. [1] among others.

3.2 Allocation of Transmission Capacity in the Different Timeframes

Transmission capacity needs to be allocated over different timeframes. As already argued, renewable, and, to some extent, conventional generators may need to get access to the grid already in the long and medium term, especially those that are located in areas that are weakly connected to main load centers. At the same time, in the short term physical access to the grid must be managed either separately from the energy dispatched or in an integrated fashion.

In the long-to-medium term, the total amount of transmission capacity to be made available for the first time in each auction should be conditioned by the demand of this capacity. Otherwise, if agents are not able to efficiently arbitrage capacity prices in auctions in different time frames, differences that are not fully justified in the price paid for transmission capacity among different timeframes may occur, which would decrease the efficiency of the allocation of transmission capacity. See [20] for a discussion of the distribution of available transmission capacity among the different timeframes. In a context with a very high penetration of RES-based generation, the appetite of RES and other generators for transmission capacity in the long term may probably increase in order to shield their commercial position. This should certainly condition the distribution though time of the issuance of available transmission capacity.

In the very long term, transmission contracts should be already allocated to agents within the transmission expansion problem. Obviously, the total amount of existing transmission capacity plus the possibility to build new one should be considered in this timeframe. The demand for these types of contracts, together with the expectations of the development of generation and demand, should condition the amount of new transmission capacity to be built. Then, in the medium-to-short term, transmission capacity should be allocated in line with the level of prices in each auction, with probably a larger amount of transmission capacity sold further ahead of real time for agents to match their long-term energy positions.

In the very short term, given the large uncertainty faced by most generation (which is expected to be RES-based) about their available production capacity, the energy dispatch should be shifted as close to real time as it is feasible, so that imbalances faced by these generators are as small as possible. If the energy dispatch is delayed and moved closer to real time, the same should be done for the short-term auction of physical transmission capacity. The larger the lapse of time between the allocation of the use of transmission capacity and the energy auction, the larger the differences between conditions applying in both auctions may be, which results in a decrease in the efficiency of the whole process. Several investigations have concluded that, if possible, energy and transmission capacity should be auctioned jointly in the very short term, see [11].

3.3 Regulation of the Connection to the Grid

Wind and solar generation have zero variable costs, and therefore a natural priority in economic generation dispatch. On top of this, under some regulations RES-based generation has traditionally enjoyed in many systems priority in the access to the grid in real time regardless of the economic implications, which sometimes can be negative. This may more easily occur when large amounts of RES-based generation exist. Only when the grid cannot safely absorb the output of RES-based generation, RES should not be allowed to produce.

In the long term, transmission capacity reserve may probably not need to take place. Capacity reserve systems provide generators that connect to the grid with the certainty that other, more efficient, generators being installed afterwards in the same node or area of the system (generation pocket) will not replace them in the energy dispatch. This encourages the installation of these first generators. However, capacity reserve mechanisms represent an obstacle to the installation of more efficient generators, since their connection in some interesting areas may not be allowed, or they will be facing frequent curtailment.

Instead, those agents wanting to ensure access to the transmission grid at the connection point of their choice shall be able to sign long-term transmission contracts. These contracts would probably be of more use for RES-based generators. Secondary markets for that products and “use-it-or-lose-it” clauses will ensure more flexible and efficient use of transmission capacity than capacity reserves mechanisms.

4 Allocation of the Cost of the Transmission Network

If intensive use of the best renewable resources is made, new generator connection lines and related system upgrades are likely to be more expensive on average than they have been historically. In addition, lines linking different areas in a region or different regions will probably be larger as well, since RES-based generation will probably be located far away from load centers. Hence, significant investments will take place in network assets to be used at regional or multinational level, i.e. affecting more than one area or system. This implies that rules used to allocate the cost of these lines among areas, regions and countries will be under scrutiny by all systems in the region. Unless regulatory authorities in the different systems of a region believe that they are paying a fraction of the cost of these lines that is commensurate with the benefit they are obtaining from them, they will oppose the construction of these lines. Then, network assets that are highly needed will not be built.

Therefore, developing an efficient allocation scheme that sends appropriate locational signals to new generators and loads is central to reducing the cost of required network reinforcements, which will also be critical in achieving their construction given the large scale of investments envisaged and existing budget constraints. In the following paragraphs we shall describe what should be the basic features of a network cost allocation mechanism in order for its results not to be challenged by affected parties. Desirable properties of a cost allocation scheme from its conception to its implementation are also discussed in [19, 25].

4.1 Allocation to Beneficiaries

Computing a fair allocation of the cost of transmission assets involves making shares of the costs born by agents or areas proportional to benefits. Beneficiaries are any network users whose expected expenditures or profits change as a result of the project, taking into account the value of increased reliability and any other not-purely economic benefits. This principle has been accepted in numerous systems. Estimates of the benefits that agents will obtain from network reinforcements must somehow be taken into account in the planning process.

A transmission project is economically justified if the benefits it creates exceed its costs. But benefits may be either positive or negative (losses). Reinforcements normally reduce price differences among the parts of the system by increasing the price of exporting areas and reducing it in importing ones. Then, a transmission project could result in losses on generators in previously high-price areas or on load in previously low-price areas. In addition, because of the aforementioned reduction in price differences, these projects may reduce the economic value of any existing transmission rights and contracts. What is more, some entities might suffer losses because of environmental harm. Regulators should approve regulated network reinforcement projects with positive net benefits that exceed investment costs, even if they cause losses on some agents. However, they should disapprove projects with gross benefits that exceed the investments costs, but whose net benefits, once considered the negative ones, are below the investment costs. This means not allowing the construction of some projects for which those who receive benefits would be willing to cover the costs.

Dividing a project's costs among network users in proportion to their benefits is generally perceived as equitable. And if a project's benefits exceed costs, all beneficiaries will be better off and less likely to oppose progress on the project. Conversely, if a project's costs exceed its benefits, it will be impossible to allocate costs in such a way as to make all entities better off. Thus, adopting the beneficiary-pays principle should help to achieve the green light from relevant partners to needed projects. Note that failure to consider all positive and negative benefits in the cost allocation process could result in some agents blocking the construction of lines. Thus, even if some benefits are difficult to monetize, like the environmental or visual impact of lines built in an area, an effort should be made in this regard.

An alternative to the beneficiary-pays principle is the socialization of investment costs. Socialization does not produce locational signals driving the decision of agents on where to install generation or load. Thus, socialization favors the best wind or solar resources, regardless of their location and impact on transmission costs, which is inefficient. Additionally, spreading costs too widely reduces cost discipline and eliminates the incentive to consider economic alternatives to transmission expansion, since socializing the costs of these alternatives would call for significant changes in decision-making in the electric system and put many important investment decisions into the hands of regulators. Finally, uniform unit charges may raise the opposition to beneficial investments by parties forced to shoulder costs that significantly exceed the benefits they realize.

Socialization may produce a similar cost allocation to the application of the beneficiary-pays principle when much uncertainty exists in the estimation of beneficiaries. This may be the case of reliability driven investments. Great uncertainty about benefits and beneficiaries generally implies that expected benefits are widely distributed. However, results of allocation to beneficiaries are still different from cost socialization in the more common cases where significant uncertainty about some beneficiaries is accompanied by less uncertainty about others.

In liberalized markets both generation and load generally benefit from new transmission capacity. Generators make profits from using the transmission system to deliver their product to other parts of the system and should therefore pay a fraction of the network costs. Load also benefits from new transmission through reduced energy prices, increased reliability, or both. Cost-allocation procedures should split costs of a line between generation and load proportionally to the aggregate economic benefits realized by the two groups. If wholesale markets are highly competitive and there is no generator that can capture extra rents, all costs levied on generators end up being passed on to load via wholesale electricity prices, either in the short or in the long term. This occurs even if network charges are levied as an annual lump sum or on a per megawatt basis rather than per megawatt-hour of produced energy. However, some generators enjoy unique advantages specific to their location or perhaps some special access to cheap fuel resources; many others do not operate in highly competitive environments. Under any of these two circumstances, generators can be charged transmission costs without any anticipated pass-through to consumers.

Undesirable consequences of the allocation of the costs of new lines according to other criteria than the benefits they produce include, for instance, abandoning socially beneficial investments in generation when the cost of long connection lines is charged 100 % to the generators involved, or eliminating locational signals to generators if too much of the transmission cost is allocated to load. The latter is especially harmful for RES generation that requires costly transmission investments. Locational signals to generators help to ensure that the most efficient sites from a system economic point of view are chosen for generator development. Despite creating inefficiencies, generators are, at least initially, responsible for the entire cost of radial interconnection lines in many systems, while load entirely bears the cost of other network reinforcements.

Any transmission planning exercise should look for investments with the largest margin of resulting benefits (or reduction in system costs) over network costs. A sound planning process must provide sufficient information on the identities of the beneficiaries of proposed transmission investments to enable those proposals to be evaluated. Transmission is inherently about moving electric power between locations, and the analysis of the value of such investment requires calculation of locational impacts on generation and load. In principle, this information should be useful to allocate costs according to the beneficiary-pays principle, though benefits may be computed jointly for bunches of investments making expansion plans. Then, allocating the benefits of specific investments to agents may probably require determining which of the benefits of a whole expansion plan are caused by each specific investment in the plan.

4.2 Transmission Charges Should Be Independent of Commercial Transactions

Given that transmission charges should be levied on those who benefit from the existence of any given transmission facility, tariffs should depend on the location of the users in the network and on the expected temporal patterns of power injection—for generators—and withdrawal—for loads—, but not on the commercial transactions—that is, who trades with whom—. This means that a generator located in a system A that trades with a load serving entity in a system B should pay the same transmission charge as if, instead, it were contracted to supply a neighboring load sited within its own system. This principle follows from what is called “the single system paradigm”: if open network access exists and there are no barriers to system-wide trade, the decentralized interaction between systems and their agents should ideally be identical to the outcome of a system-wide efficient generation dispatch, regardless of who trades with whom. The independence of the transmission charges from the commercial transactions directly follows. The application of this principle should not be affected by the existence of any contracts signed by any agents, since they should modify neither the physical real-time efficient dispatch of generation nor the demand.

Failure to make transmission charges independent from commercial transactions can result in “pancaking” or piling up of transmission charges, where network users are required to pay accumulating fees including those for the areas through which their power is deemed to pass between the buyer and seller. Pancaking makes transmission charges depend on the number of administrative borders between buyer and seller. Such pricing tends to stifle trade and to prevent buyers from accessing low cost sellers. The resulting perverse incentives could lead to inefficient transmission investments and would significantly complicate operations in networks. Pancaking has traditionally occurred in both the EU and the US. It has been banned in the IEM of the EU about 10 years age, but may still occur in interregional trade in the US.

4.3 Computation of Transmission Charges Once and for All

Transmission network charges for new network users should be computed before the latter are installed and should not be updated, or at least not for a reasonably long time. This is the only way to send the reliable economic locational signals that investors need to take into account to choose the most convenient sites with a low financial risk. This is of particular interest for wind and solar generators, which may be installed in many sites.

Locational signals are meant to encourage potential new generators to be placed at convenient locations from the transmission network viewpoint, i.e., where the presence of the new generator will reduce (or, at least, not increase) the need for network reinforcements. Transmission charges may also affect the retirement decision of old plants with scant profit margins. No significant impact is expected on the siting decisions of consumers, since transmission charges are a minor part of the total electricity costs they bear, which normally is not a major ingredient of the consumers' budget.

Given that no locational impact is possible for new generation investments once they are into the construction period or in operation, when a new generator requests connection to a certain point of the grid, the System Operator should inform him of the transmission charges to be levied on him for the next 10 years (or a similar figure). Due to the uncertainty surrounding most of the major factors that affect the profitability of power plants, having certainty over the first 10 years of operation should be enough for the investor to decide whether to build the new generator in a certain place or not. Additional information acquired by the TSO/SO during year T should not be reflected in charges to be paid in the following 10 years by users installed in T, but could be used to update the trajectory of network charges that will be announced at the beginning of year T + 1 and applied to any new entrants.

The existence of large amounts of RES generation will make it more difficult to predict conditions applying in the future, as it is the case of economic dispatch. Then, due to the inability to appropriately predict network use, transmission tariffs computed ex-ante will be less efficient than in the case where RES penetration is lower, since they will be less likely to reproduce future system conditions; on the other hand, updating network charges periodically defeats their main purpose of sending credible locational signals to prospective investors.

4.4 Format of Transmission Charges

The choice of format for the transmission charges has implications on the short- and long-term behavior of the agents of the market. For instance, a volumetric transmission charge (€/MWh) to generators becomes an additional component of their variable production costs, therefore distorting the economic dispatch of generation, since it introduces a spurious component in the variable costs. On the other hand, a capacity charge (€/MW) to generators will have to be considered as an additional fixed cost for investors in new generation facilities. Uniform capacity charges will unduly harm the interests of peak generators favoring base load ones. Their size and location being equal, a base load generator will make a larger use of the network, and obtain larger benefits from it, than a peak load one producing just a few hours in the year. Thus, transmission charges applied should be structured as fixed payments that are specific to each generator or consumer or, alternatively, as capacity ones that are dependent on the location and generation technology, or type of consumer.

4.5 Allocation of Costs in Regional Markets

The existence of RES generation is expected to result in an increase in flows among areas in a region in most scenarios that can be envisaged for the future. Then, a large fraction of grids will be used by external agents, which calls for the development of pan-regional tariffs or compensation schemes. Mechanisms implemented for the allocation of the cost of new network reinforcements at regional level should result in countries or systems in the region paying a fraction of the cost of the grid that is commensurate with the benefits they perceive they are obtaining from these reinforcements. Otherwise, these countries may oppose the construction of these transmission facilities, which may be badly needed by the region as a whole, among other things, to realize the integration of RES generation required to achieve environmental policy objectives, see [18]. As discussed above, if proper mechanisms, based on beneficiaries, are not applied centrally at regional level to allocate the cost of all network investments, then some ad hoc mechanism should be applied when allocating the cost of large network infrastructures of a regional (cross-border) nature. The latter could result in side-compensations among countries. These side-compensations should be paid by those countries or systems mainly benefiting from relevant network investments to those other systems that would not benefit significantly from these investments but would have to bear a significant part of the costs of any kind associated with these projects.

Additionally, given that generators, at least large RES-based ones, are competing at regional level by selling their output in other areas in the system than those where they are located, achieving a level playing field among these generators also calls for computing network tariffs to be paid by all of them in an integrated manner through the application of a common charging scheme or, at least, through the harmonization of certain aspects of the computation of tariffs. Minimum aspects to harmonize should include the fraction of the cost of the grid to be levied on generators within each system, since generators and large consumers are those network users whose economic decisions are most affected by the level of electricity tariffs (and within them transmission charges) they have to pay, and the structure of tariffs in order for transmission charges, which are aimed at recovering costs incurred in the long term, not to affect operation decisions by agents, which are short term. However, applying the cost allocation principles outlined in Sects. 4.1–4.4 is also deemed necessary.

5 Conclusions

Integrating large amounts of RES generation capacity is needed to achieve long-term environmental policy objectives. Due to the specific features of this type of generation, namely the variability and unpredictability of its output, and the uneven distribution of primary RES over a region, the regulation of the transmission activity will have to be adapted accordingly.

Changes required concern the main aspects of the functioning of the transmission activity. The expansion of the grid will need to be centrally planned and managed so as to consider benefits exceeding the borders of each system or country. At the same time, new transmission products, long-term contacts, will be needed to create attractive enough investment conditions for RES and conventional generation promoters. Network expansion planning algorithms will need to be improved to be able to consider larger regional systems and a larger multiplicity of operation situations.

The allocation of any scarce transmission capacity will have to take into account the need to facilitate transmission contracts in the long term to the generators. The distribution of the total amount of transmission capacity to be auctioned in the different timeframes will have to be reconsidered. A large fraction of capacity should be allocated in the long term in the form of contracts. Short-term transmission capacity allocation would occur, probably jointly with the energy dispatch, just before real time, so that the considered output profile of RES generation is as close as possible to the actual one. The regulation of connection to the grid shall also be conditioned by the concession of the already mentioned long-term transmission contracts.

Lastly, the allocation of the costs of the transmission network shall be based on cost allocation principles that have already been widely discussed. However, the existence of RES generation, and the accompanying large power flows covering large distances, will make the application of these principles absolutely necessary in order not to jeopardize RES generation deployment. Thus, the allocation of the cost of large new network infrastructures of a regional nature should be based on the application of the beneficiary-pays principle; charges paid by network users should be computed once for large periods of time and should not depend on commercial transactions; transmission charges should be structured as fixed payments, not allocated as per energy or per capacity; and transmission charges applied in a region should be harmonized so that differences among charges do not hamper competition among regional generation operators.

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Measuring Performance of Long-Term Power Generating Portfolios

José M. Chamorro, Luis M. Abadie and Richard de Neufville

Abstract We propose a model for assessing the performance of generation mixes in a mean-variance context. In particular, we focus on the expected price of electricity and the price volatility that result from different generating portfolios that change over time (because of investments and retirements). Our valuation model rests on solving an optimization problem. At any time it minimizes the total costs of electricity generation and delivery. A distinctive feature of our model is that the optimization process is subject to the behavior of stochastic variables (e.g. load, wind generation, fuel prices). Thus we deal with a problem of stochastic optimal control. The model combines optimization techniques, Monte Carlo simulation over the decades-long planning horizon, and market data from futures contracts on commodities. It accounts for uncertain dynamics on both the demand side and the supply side. The aim is to assist decision makers in trying to assess electricity portfolios or supply strategies regarding generation infrastructures. To demonstrate the model by example we consider the case of Great Britain's generation mix over the next 20 years. In particular, we compare three future energy scenarios and the contracted background, i.e. four time-varying generating portfolios. Major British power producers are covered by the EU Emissions Trading Scheme (ETS), so they operate under binding greenhouse gas (GHG) emission constraints. Further, the UK Government has announced a floor price for carbon in the power sector from 1 April 2013. The generation mix is optimally managed every period by changing input fuel and electricity output as required.

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1 Introduction

Investments in power generation usually entail two types of effects: (i) *portfolio* effects, i.e. the interplay between a new power plant and the existing fleet of plants owned by a utility or located in a country; and (ii) *option value* effects, e.g. the flexibility to run on particular technologies at a higher or lower rate over time as uncertainty about the future unfolds. It has long been recognized that a proper valuation of investments in power generation needs to capture both effects [7]. In other words, if the optimal degree of fuel mix diversity is to be identified, we need valuation approaches that trade-off the expected returns and risks of increased portfolio diversification, in both a static and dynamic perspective.

Mean-Variance Portfolio (MVP) theory is well suited for the first task [25]. The standard framework envisages an investor that is confronted with a (financial) portfolio selection problem. As long as information about asset average returns, variances, and covariances is available, it is possible to map the whole set of assets and portfolios of assets on a risk/return diagram. Hence, provided the investor dislikes risk and likes return, it is possible to delineate the *efficient frontier*, i.e. the set of asset portfolios that either minimizes risk for a given level of expected return, or maximizes the latter for a given level of the former. Thus MVP theory allows investors to identify the range of efficient choices. Then it is up to the investor to identify the particular portfolio that best matches her/his individual preferences regarding expected return and risk (the *optimal portfolio*). MVP theory thus improves decision making in two ways: (i) by simplifying the portfolio selection problem (narrowing down the choice along the efficient frontier), and (ii) by sticking a number to the reduction of risk that diversification brings about.

MVP theory has been applied to real assets such as power plants with the aim of identifying the optimal portfolio of generation assets for a utility or a country [2–4, 8, 20, 21, 32]. Bazilian and Roques [7] provide a brief review of this literature alongside a number of state-of-the-art applications of MVP theory for electric utilities planning. Early MVP applications mostly took a national or societal perspective; they were based on power generating cost and concentrated on fuel price uncertainty. Some recent studies have instead adopted the viewpoint of private investors. Therefore they also take account of a broader set of risks: electricity price, emission allowance price, the co-movement of fuel, electricity, and carbon prices, among others.

In dynamic, uncertain environments the availability of a broad range of generation technologies and the flexibility to run on them at different rates are particularly valuable. However, this value is elusive. The Real Options approach (ROA) aims to quantify the value of a number of options that (project) managers have at their disposal (e.g. the investment timing, size, stages, and so on). See Dixit and Pindyck [14] and Trigeorgis [34].

When it comes to applying ROA to inform investments in power technologies, it is usually necessary to adopt relatively restrictive assumptions about the stochastic behavior of commodity prices. Besides, futures contracts on those commodities may well be available but their liquidity for the decades-long maturities that these infrastructures typically involve may falter. For a sample of ROA applications see Murto and Nese [26], Roques et al. [31], Nässäkälä and Fleten [27], Blyth et al. [9], Abadie and Chamorro [1].

Investors in liberalized electricity markets are naturally concerned about the expected return and the risk of their investments. At the same time, policy makers may guide investments in power plants in a particular direction (e.g. by adopting a societal, as opposed to private, perspective). We propose a model for assessing the performance of dynamic generation mixes in a mean-variance context. In particular, we focus on the expected price of electricity and the price volatility that result from different generating portfolios that change over time (because of new investments and decommissioning of old plants).

There is a stark difference between our approach and the MVP portfolio approach. The latter typically aims to identify a set of efficient fuel mixes that optimally trade off the risks and expected returns of diversified portfolios of generating plants. This 'efficient frontier', however, usually corresponds to a single-period uncertain situation, i.e. adopts a static perspective. Instead, we develop a dynamic, multi-period approach. We assess the performance of different generating mixes over decades. Similarly to the mean-variance approach, we can restrict ourselves to considering a handful of particular generation settings which are of interest to industry or policy makers. Our two measures can be plotted in the standard risk-expected cost (or return) space, just like in the portfolio approach. But they tell a rather different story, namely how our time-varying 'portfolios' behave over a multi-year period (in terms of electricity price).

The model comprises two stages, namely simulation and optimization. The optimization model minimizes an objective function subject to constraints. The objective function considers two kinds of system costs: those of electricity generation and of unserved or lost load. The constraints can be split into two blocks concerning the physical and economic environment. Regarding physical uncertainty, power infrastructures are subject to failure. As for economic uncertainty, commodity prices display mean reversion and seasonality where appropriate. Load is similarly assumed to be seasonal and stochastic. The optimization provides, at any time, the level of generation from each technology and served load along with aggregate generation costs, carbon emissions, and allowance costs. We consider a 20-year time horizon (the one adopted in the UK Future Energy Scenarios). Over this period the network topology changes naturally as new stations start operation while others are decommissioned. Each year is broken down into 60 time steps (5 per month); i.e. the relevant period for the optimization problem is 1/60 year.[1]

The optimization model is nested in Monte Carlo simulation. Needless to say, if simulations are to be realistic then we must work with numerical estimates of the underlying parameters from official statistics, market data, and the like. A single run determines the operation state of generation infrastructures over 60 × 20 = 1,200 consecutive time steps. The same holds for the value of stochastic load, wind- and hydro-based generation, fossil fuel prices, and carbon price. Under each setting, the optimization problem is solved: depending on the circumstances in place, generation is optimally dispatched subject to the network topology. Therefore, one simulation run involves 1,200 optimizations. We repeat the sampling procedure 750 times (so we solve 900,000 optimization problems). We thus come up with 750 time profiles of each variable of interest. Out of these simulations, we can determine several metrics (not only averages) and derive the cumulative distribution function of effects over major variables.

Therefore our model can assess the performance of a pre-specified generation fleet in terms of the resulting expected price and the standard deviation around that expectation. These two pieces of information fall naturally within the MV approach to portfolio theory. At this point, it is possible to assess the performance of the whole system (under different generation mixes) according to several other metrics, e.g. operation costs, unserved load, carbon emissions, etc. Comparing their relative performance sheds light on their respective advantages and weaknesses.

Of course, uncertainty about the future affects the rate at which future cash flows must be discounted to the present. Some related papers develop their analyses under two (or more) discount rates, e.g. Roques et al. [32]. Another usual practice is to assume a particular utility function that characterizes the tradeoff between risk and return [22]. One of the inputs to this function is the coefficient of risk aversion. Analyses are then developed under two, three or more levels of risk aversion [16, 33, 38]. In our approach, futures markets play a major role. In addition to their informational role, the use of futures prices allows discount at the risk-free interest rate. This fact sidesteps the discussion about the appropriate discount rate.

To demonstrate how the model works we undertake a heuristic application. In particular, we consider the UK Future Energy Scenarios up to 2032. We consider both base- and peak-load technologies, and also installed capacities of power technologies as scheduled by the UK Department of Energy and Climate Change (DECC) over the planning horizon (2013–2032). The UK is covered by the EU Emissions Trading Scheme (ETS), so their electricity generators operate under

[1] This is in contrast to related papers that usually perform economic dispatch on an hourly (or shorter) basis with a time horizon extending over one (or a few) year(s). For example, Delarue et al. [12] take hourly load patterns into account (over 7 weeks) and corresponding dispatch issues as ramping constraints. There would be no major problem in using our model for a yearly period on an hourly basis (8,760 steps) apart from the increase in the time required for computation. Unfortunately, our long-term simulation comes at the cost of framing the optimization problem on a longer time span (for example, a week instead of an hour).

binding greenhouse gas (GHG) emission constraints. Note that the UK Government has announced a floor price for carbon in the power sector from 1 April 2013 with an initial value around 16 £/tCO2 to target a price for carbon of 30 £/tCO2 in 2020 and 70 £/tCO2 in 2030. Each generation portfolio is exogenously given but is optimally managed by changing input fuel and electricity output as required.

The paper is organized as follows. Section 2 introduces the theoretical model. Upon the distinction between the physical environment and the economic environment it presents the optimal dispatch problem. Then Sect. 3 shows a heuristic application to four dynamic generating portfolios assumed to provide a range of potential paths of Great Britain over the period 2012–2032. A section with our main findings concludes.

2 The Model

We propose a model for evaluating the performance of time-varying generation portfolios. The performance depends on factors that change over time, e.g. network topology, market structure, fuel and electricity prices, energy policy, environmental and climate policies, etc. Our valuation model rests on solving an optimization problem. At any time it minimizes the total costs of electricity generation and delivery; in this sense it draws on Bohn et al. [10]. A distinctive feature of our model is that the optimization process is subject to the behavior of the stochastic variables (e.g. load, fuel prices); thus we deal with a problem of stochastic optimal control, which is similar to that in Chamorro et al. [11]. We allow for the possibility that a fraction of the demand is unserved, but this has a non-negligible cost (thus, with the exception of extreme cases, in practice load is always served). Regarding market power or strategic bidding by power generators, we account for these issues through the profit margin of the electricity price-setting (or 'marginal') technology.[2]

The model allows for random failures in physical facilities. Uncertainty stems also from load, wind generation, and hydro generation. We assume these follow stochastic processes with suitable properties (for example, seasonality or stationarity) that can be estimated from official statistics. Stochastic processes similarly govern the economic sources of uncertainty (fossil fuel prices and allowance prices). For estimation purposes, the ideal market data are composed of futures prices; this is important because (assuming the required liquidity/maturities are met) they enable us to estimate parameter values in a risk-neutral setting.[3]

Our model does not address the question of the optimal time to alter the generation portfolios. We ignore inflation and efficiency targets at this stage. We abstract from access-pricing problems for new generators. The model allows a number of questions to be modeled and answered. Thus, in our base case climate

[2] See Chamorro et al. [11], Appendix C.

[3] This does not mean that investors are risk neutral.

policy makers commit themselves to a certain future path of the allowance price by setting a floor (i.e. carbon price evolves stochastically but always above a minimum threshold level). We run the model to assess the overall impact (both absolute and relative to the case without a floor price). Besides, we try different time-varying portfolios of generation facilities. This way the model can assist decision makers when confronted with challenging strategic choices.

We aim to evaluate the performance of long-term portfolios through the resulting electricity price and its volatility alongside the abatement of CO_2 emissions. Since the probability distribution of these impacts can be asymmetric, we go beyond average values and derive whole distributions of effects. The electricity prices in particular can be used to check whether they are high enough to get a fair return on investments in any particular type of power technology.

The optimal power flow (OPF) algorithm dispatches generation assets in merit (least-cost) order subject to physical constraints. The economic dispatch problem is to find output for each available technology so as to minimize total (system) costs while meeting load plus line losses. At every time demand and supply must be balanced, and the Laws of Physics must apply in the network.

2.1 Physical Environment

Load. Load is assumed inelastic and stochastic while showing seasonality. D denotes the net demand for electricity from consumers. Pumped storage is a power technology that effectively consumes electricity; its contribution, P, has a negative sign. Therefore, the gross demand d is the sum of the realizations of two different stochastic processes computed as:

$$d = D + P.$$

Depending on the infrastructure available, load can be fully served or not. The electricity actually served is denoted by s.

Future demand dispalys seasonality and is uncertain. We assume that the deseasonalized load evolves over time according to the following Inhomogeneous geometric Brownian motion (IGBM):

$$\mathrm{d}D_t = k(L - D_t)\mathrm{d}t + \sigma D_t \mathrm{d}V_t,$$

D is assumed to show mean reversion. L is the long-term equilibrium level toward which the present deseasonalized load tends. k is the speed of reversion toward that "normal" level. The instantaneous volatility of this load is denoted by σ. $\mathrm{d}V_t$ is the increment to a standard Wiener process; it is normally distributed with mean zero and variance $\mathrm{d}t$.

Generation capacity. S stands for a given particular power station, and its actual electricity generation is denoted by x with an upper bound $\bar{x}$.

The coal (c), natural gas (g), and nuclear (n) fuel technologies in our model are prone to failure. We adopt a set of binary (Bernoulli) random variables for the possibility of any one contingency. We thus assume that each station S of type $\{c, g, n\}$ is in service for a fraction Λ of the year. Here $c = \left\{1, \ldots, \overline{C}\right\}$ stands for coal plants, irrespective of whether they are operative or not. Note that $\overline{C}$ is not fixed; it can change over time due to openings or closures on a planned schedule. Similarly, $g = \left\{1, \ldots, \overline{G}\right\}$ and $n = \left\{1, \ldots, \overline{N}\right\}$ refer to gas and nuclear plants.

We do not consider that wind (w), natural-flow or hydro (h), and pumped storage (p) stations can be 'off'. All the intermittences for whatever reasons are modeled through the stochastic behavior of the load factor. The theoretical model assumed is an IGBM:

$$\begin{aligned} \mathrm{d}W_t &= k_W(W_m - W_t)\mathrm{d}t + \sigma_W W_t \mathrm{d}Y_t^W; \\ \mathrm{d}H_t &= k_H(H_m - H_t)\mathrm{d}t + \sigma_H H_t \mathrm{d}Y_t^H; \\ \mathrm{d}P_t &= k_P(P_m - P_t)\mathrm{d}t + \sigma_P P_t \mathrm{d}Y_t^P. \end{aligned}$$

The standard notation for reversion speed, long-term value, and volatility holds (wind: k_W, W_m, and σ_W; hydro: k_H, H_m, and σ_H; pumped storage: k_P, P_m, and σ_P).

Generation from wind, natural flow and pumped storage stations is seasonal. Our simulations assume a seasonal behavior for renewable electricity, so the seasonality in each load factor must be previously identified (from historical time series).

We can define the activity vector $a \equiv \left\{a_c, a_g, a_n, 1, 1, 1\right\}$ across all its technologies $f = \{c, g, n, w, h, p\}$. Aggregate output electricity, denoted x, comprises generation from all its energy sources $f = \{c, g, n, w, h, p\}$:

$$x \equiv \sum_f x_f = x_c + x_g + x_n + x_w + x_h + x_p.$$

The maximum power that can be generated at a given time (t) by coal plants is $a_c \bar{x}_c$. Therefore, the aggregate output electricity is bounded from above.

2.2 Economic Environment

Demand-side costs. According to Foley et al. [15], in liberalized electricity markets the sale of electricity at a profit is the main business focus with value of lost load (VOLL) playing a larger part than energy not served (ENS) (which was a key factor in the era of the state monopoly). Short run marginal cost-based pricing is generally not high enough to ensure this, so equilibrium involves a degree of ENS priced at

VOLL. Thus in our model we have implicit rationing costs. The overall unmet load is computed as:

$$d - s.$$

All consumers are assumed to have an identical and constant VOLL per unit, VOLL, for any level of electricity use. Thus demand-side costs equal the above difference times VOLL.

Supply-side costs. A major driver of stations' short-term marginal costs is fuel cost (in addition to emissions cost). We assume that wind, hydro and nuclear stations bid a price of zero [37]; that pumped storage takes electricity from the network at the bottom of the price range; and that the prices of coal (C), natural gas (G), and carbon dioxide (A) evolve stochastically over time.[4]

In a deregulated electricity market, economic costs include both explicit input (fuel) and output (emissions) costs, and a margin to get a 'reasonable' profit for the generation units. Its size (here assumed constant) crucially depends on the 'marginal' technology that sets the electricity price, and the scope for market power and/or strategic behavior by generators.

Generation costs comprise the (bid-based) costs incurred by all power technologies $f = \{c, g, n, w, h, p\}$. Since wind, hydro, and nuclear generators are assumed to bid a zero electricity price, these sources will be fully dispatched whenever available as long as load surpasses their availability: $x_w = \bar{x}_w$, $x_h = \bar{x}_h$, $x_n = \bar{x}_n$. Noting that pumped storage stations tend to adjust their operation to the time when electricity prices are at the higher end, even above natural gas turbines, we assume their 'cost' function is a multiple of that of gas turbines, in our case, 1.10. Thus total generation costs are:

$$\begin{aligned} c(x) = & x_c\left(M_m + \frac{C + 0.34056A}{H_C}\right) \\ & + x_g\left(M_m + \frac{G + 0.20196A}{H_G}\right) + x_p 1.1\left(M_m + \frac{0.20196A}{H_G}\right). \end{aligned}$$

Here H_G and H_C denote the thermal efficiency of gas- and coal-fired stations, respectively. C and G denote the price (in €/MWh) of coal and natural gas, respectively, while A stands for the price (in €/tCO2) of carbon dioxide. In electricity markets where natural gas-fired stations are the usual marginal technology, the fixed margin M_m will be the 'average' or long-term clean spark spread.[5] When coal-fired plants or pumped storage stations are the marginal plants, we assume that they earn the same margin.

[4] When there is a floor price for carbon in place (as in the UK), the carbon price (A) can be different from the allowance price on the EU ETS.

[5] As shown in National Grid [28], both peak and baseload electricity prices more or less track natural gas prices at National Balancing Point (which does not happen with coal or oil, for instance). This is relevant when we deal with the profit margin included in generation costs; see Chamorro et al. [11], Appendix C.

We assume that natural gas prices display a seasonal pattern, but that coal and carbon do not. The long-term prices of natural gas and coal are described by the following IGBM stochastic processes in a risk-neutral world:

$$\mathrm{d}G_t = \mathrm{d}f_G(t) + [k_G G_m - (k_G + \lambda_G)(G_t - f_G(t))]\mathrm{d}t + \sigma_G(G_t - f_G(t))\mathrm{d}Z_t^G.$$
$$\mathrm{d}C_t = [k_C(C_m - C_t) - \lambda_C C_t]\mathrm{d}t + \sigma_C C_t \mathrm{d}Z_t^C.$$

Unrestricted carbon prices (e.g. those on the EU ETS) are assumed to follow a standard geometric Brownian motion (GBM):

$$\mathrm{d}B_t = (\alpha - \lambda_B)B_t\mathrm{d}t + \sigma_B B_t \mathrm{d}Z_t^B.$$

Nonetheless, the UK has set a floor that effectively supresses downward paths below a certain limit. Therefore, the (restricted) time-t allowance price A_t that serves as the basis for computing A_{t+1} in our simulations obeys the scheme:

$$A_t = \mathrm{floor}(t) + \max(B_t - \mathrm{floor}(t); 0).$$

Thus, if $B_t >$ floor(t) the restricted carbon price and the unrestricted one are the same: $A_t = B_t$. Conversely, if $B_t <$ floor(t) then we have $A_t =$ floor(t).

Both G and C are assumed to show mean reversion. G_m and C_m denote the long-term equilibrium levels toward which current (deseasonalized) gas and coal prices tend in the long run. $f_G(t)$ is a deterministic function that captures the effect of seasonality in gas prices. k_G and k_C are the reversion speeds toward the "normal" gas and coal prices. Regarding the price of the emission allowance, the parameter α stands for the instantaneous drift rate of carbon price. σ_G, σ_C and σ_B are the instantaneous volatility of natural gas, coal and carbon allowance. λ_G, λ_C and λ_B denote the market price of risk for gas, coal, and allowance prices. $\mathrm{d}Z_t^G$, $\mathrm{d}Z_t^C$ and $\mathrm{d}Z_t^B$ are the increments to standard Wiener processes. They are normally distributed with mean zero and variance dt; besides:

$$\mathrm{d}Z_t^G \mathrm{d}Z_t^C = \rho_{GC}\mathrm{d}t; \mathrm{d}Z_t^G \mathrm{d}Z_t^B = \rho_{GB}\mathrm{d}t; \mathrm{d}Z_t^C \mathrm{d}Z_t^B = \rho_{CB}\mathrm{d}t. \quad (3)$$

From the above stochastic differential equation for a commodity price under risk neutrality it is possible to derive a theoretical model for the futures price with any desired maturity. We estimate the parameters in this stochastic model using daily prices and non-linear least-squares regression (see [11], Appendix D). Upon estimation of the parameters we can simulate the behavior of commodity prices any number of times.

Economic dispatch. We assume that the system operator dispatches generating resources to minimize the total costs of generation and unserved energy. As is usually the case in electricity markets, nuclear, wind and hydro are assumed to be located at the bottom end of the 'merit order', i.e. they are the first technologies to enter the system. Consequently, the problem below solves for the generation level of coal- and gas-fired power plants (x_c and x_g, respectively) along with that of pumped-storage stations (x_p) and power served (s). A high VOLL implies in practice that the load will be served unless this is not technically feasible. The aim is to find an optimal vector of power generated $\{x\}$ and power served/consumed $\{s\}$ that minimizes system costs at any time:

$$\min_{\{x_c,x_g,x_p,s\}} c(x_c, x_g, x_p) + (d - s) \times \text{VOLL}$$

Subject to:

$$\begin{aligned}
&0 \le x_f \le a_f \bar{x}_f, \;\; f = \{c, g, n, w, h, p\}; \\
&0 \le s \le d; \\
&\mathrm{d}D = a(D, t)\mathrm{d}t + b(D, t)\mathrm{d}V; \\
&\mathrm{d}R = a(R, t)\mathrm{d}t + b(R, t)\mathrm{d}Y; \;\; R = \{W, H, P\}; \\
&\mathrm{d}X = a(X, t)\mathrm{d}t + b(X, t)\mathrm{d}Z; \;\; X = \{C, G, B\}; \\
&A_t = \text{floor}(t) + \max(B_t - \text{floor}(t); 0).
\end{aligned}$$

The first two restrictions set the environment as determined by the operation state of the physical assets. The components of the power system are subject to limits. Besides, the power delivered is lower than or equal to the amount demanded. In other words, served load must fall between zero and total load (it is possible that some load is not met when cost is minimized).

The last three restrictions are the stochastic differential equations. Demand $\{D\}$ has an initial value and evolves seasonally and stochastically over time. The load factor of renewable, intermittent wind- and hydro-based generation stations $\{W, H, P\}$ is governed by a stochastic process. Similarly, the price of each commodity (coal, natural gas, and emission allowance) follows another Ito process. The increments to standard Wiener process dV, dY and dZ differ. dZ also differs for each commodity $\{C, G, B\}$ along with the terms $a(X, t)$ and $b(X, t)$.

3 A Heuristic Application to the British Power Sector

To illustrate the model by example we consider a single system that is initially given and fixed, namely Great Britain as of 2012. We abstract from the particular arrangements of the British wholesale electricity market [37], which does not operate as a pool.[6] The demonstration of our general approach is thus inspired by GB in that it uses plausible data, but with no claim as to accuracy for GB in detail.

[6] The wholesale electricity market is operated within the British Electricity Trading and Transmission Arrangements (BETTA). It is based on voluntary bilateral agreements between generators, suppliers, traders and customers. In practice BETTA does not set a unique price: the actual price generators are paid or customers have to pay is different if there is underproduction (for generators) or overconsumption (for consumers).

Table 1 GB electricity generation mix as of 2012 [29]; Contracted Background

	TEC (MW)[a]	MPP stations	Thermal eff.	Availability
Coal	27,571	22	0.360	0.75
Natural Gas	33,769	79	0.477	0.95
Nuclear	10,561	10	0.398	0.77
Wind	6,910	71		
Hydro	1,626	79		
Pumped Storage	6,380	4		

[a] 'Transmission entry capacity' (TEC) is a Connection and Use of System Code term that defines a generator's maximum allowed export capacity onto the transmission system. All companies whose prime purpose is the generation of electricity are included under the heading'Major power producers' (MPPs); they account for more than 90 % of total electricity generation. Large scale hydro, large scale wind, and some biofuels fall within this category. Most generators of electricity from renewable sources are "Other generators" because of their comparatively small size, even though their main activity is electricity generation

Regarding load, UK official statistics take 'Electricity available' as the starting point for sales of electricity to consumers. This amount reflects the contribution from all stations including pumped storage *P*. Electricity available in 2012 amounted to 336.96 TWh. After subtracting transmission and distribution losses alongside theft, sales to consumers reached 308.41 TWh.[7] Value is sacrificed whenever load is lost. We assume VOLL = 2,500 ₤/MWh interrupted [30], or 2,904.44 €/MWh.

As for the generation capacity, the second column of Table 1 shows the generation mix by fuel source as of 2012. Based on UK DECC [35], coal-fired stations reach a thermal efficiency of 36 %, combined cycle gas turbines reach 47.7 %, and nuclear stations 39.8 %. "Wind" denotes both offshore and onshore wind. "Hydro" stands for "Other renewables"; hydro stations generate electricity by flowing water through turbines from sources naturally replenished through rainfall. "Pumped storage" denotes "Other (Oil/Pumped)"; the latter stations use off-peak electricity to pump water to a reservoir. They then release water to generate electricity at times of peak demand (they are not considered to be renewable sources; UK DECC [36]). The next column shows the number of power stations owned or operated by Major Power Producers classified by type of fuel. Our model assumes a fleet of identical average plants for each technology every year. The number and type of power stations is expected to change significantly in the years ahead.

Maintenance and other works make plants unavailable from time to time. We assume that natural gas plants are available 95 % of the time; nuclear plants 77 %; and coal plants 75 %. As for renewable sources, all the stations are active in principle but are intermittent. The time series of their metered output accounts for their active/inactive state and load factor in a unified form. We use these data to

[7] UK Department of Energy and Climate Change [35], Table 5.5, support MC Excel spreadsheet.

estimate the underlying parameters of wind generation, pumped storage and hydro generation; see Appendix Tables A.3, A.5, and A.7.

Any day we have futures prices of all contracts on natural gas with monthly, quarterly, seasonal (April–September and October–March), and yearly maturities on the European Energy Exchange (EEX, Leipzig). We collected these data over 231 days. Similarly for coal to be delivered in Amsterdam, Rotterdam, or Antwerp (so-called ARA coal). We also collected the prices of futures contracts on EU emission allowances traded on the Intercontinental Exchange (ICE; London); see Chamorro (2012), Appendix D. Using the futures prices on each day and non-linear least-squares, we derived the curve that best fits futures prices on that day; this provides an estimate of the parameters in the (risk-neutral) stochastic model. Upon the calibration on each of the sample days, we computed the corresponding average values in a second step; we use them as reasonable estimates of future behavior.

Concerning the economic dispatch, the system operator aims to find an optimal vector of power generated (x) and consumed (s) that minimizes the sum of (bid-based) generation costs and unserved demand costs subject to the restrictions stated above. The number of possible states of the system is $2^{(22+79+10)}$ in 2012; this figure will change as old plants are decommissioned and new plants start operation.

Our aim is to evaluate the performance of dynamic generation portfolios. We discount future cash-flows at the risk-free interest rate using risk-neutral parameters. We run 750 simulations each consisting of 1,200 steps over 20 years (i.e. five steps per month). At each step the optimal dispatch problem is solved subject to the restrictions then in place; i.e. we solve 900,000 optimization problems that minimize the sum of the bid-based costs of electricity generation and the cost of unserved load, subject to linear and non-linear restrictions. The solution to each problem defines the levels of generation and the power effectively served. Hence we compute the bid-based production costs, electricity price, and carbon emissions, among other variables. We follow the same steps with each generation portfolio. The comparison among them describes their (relative) performance in terms of the variable(s) involved.

3.1 Future Demand: Assumptions

We collected monthly load data from January 2002 to August 2013, i.e. 140 observations; see Fig. 1. Our base case analysis assumes that electricity demand shows mean reversion over time with a null rate of growth. Transmission and distribution losses alongside theft account for 9 % of overall demand over the sample period. We estimate a load function with seasonality; see Appendix Table A.1. The model is run with the same forecast demand under all the generation mixes considered.

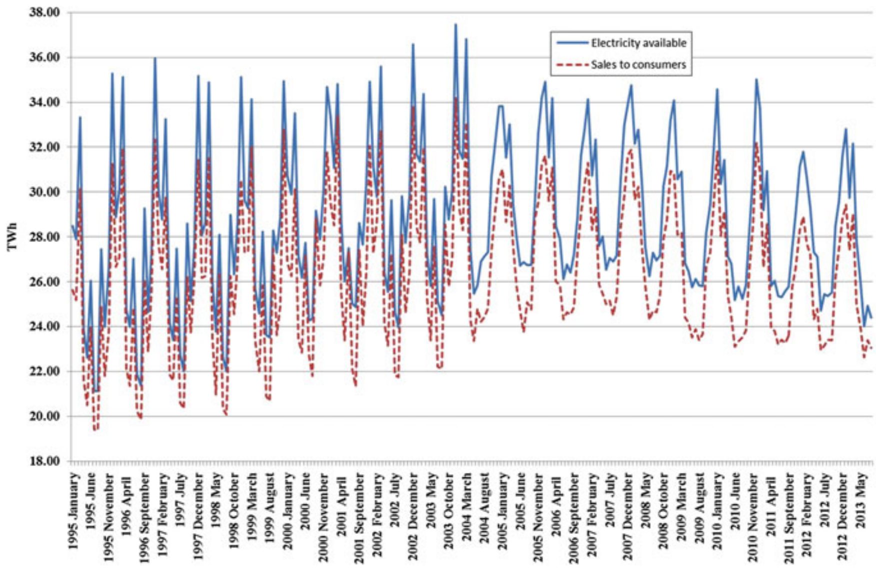

Fig. 1 Past record of UK electricity available and sales of electricity to consumers (Public distribution system)

3.2 *Future Generating Portfolios*

The UK has legislation in place setting limits on the emissions of greenhouse gases as far ahead as 2050.[8] Other legislation mandates a minimum level of renewable energy in 2020.[9] The 2012 Electricity 10 Year Statement[10] (or ETYS for short; [29] is the first GB document of its kind to be published. It forms part of a new suite of publications which is underpinned by the UK Future Energy Scenarios. The ETYS analysis is based around three future energy scenarios which provide a range of potential reinforcements and outcomes. Additionally, further analysis has focused on the contracted background, which includes any existing or future project that has a signed connection agreement with National Grid.

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[8] The Climate Change Act of 2008 introduced a legally binding target to reduce GHG emissions by at least 80 % below the 1990 baseline by 2050, with an interim target to reduce emissions by at least 34 % in 2020. It also introduced 'carbon budgets', which set the trajectory to ensure these targets are met. These budgets represent legally binding limits on the total amount of GHG that can be emitted in the UK for a given 5-year period. The fourth carbon budget covers the period up to 2027 and should ensure that emissions will be reduced by around 60 % by 2030.

[9] Renewables are governed by the 2009 Renewable Energy Directive which sets a target for the UK to achieve 15 % of its total energy consumption from renewable sources by 2020.

[10] http://www.nationalgrid.com/uk/Electricity/ten-year-statement/current-elec-tys/.

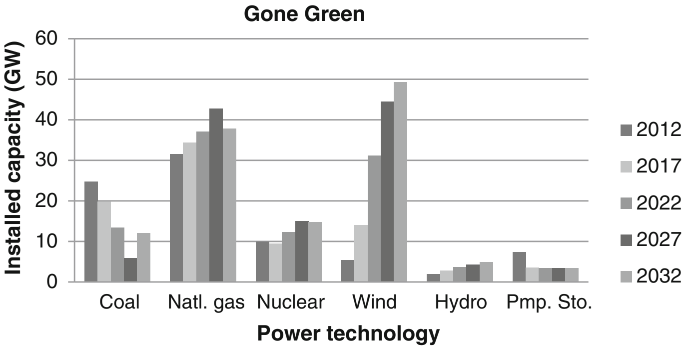

Fig. 2 Generation mix 2012–2032 under Gone Green future energy scenario [29]

Gone Green (henceforth GG). This is the main analysis case for the ETYS. It assumes a balanced approach with different generation sectors contributing to meet the environmental targets. Gone Green sees the renewable target for 2020 and the emissions targets for 2020, 2030 and 2050 all met.

As Fig. 2 shows, coal capacity decreases dramatically over the period with a U-turn as new carbon capture and storage (CCS) capacity comes on line from 2025 onwards. This is due to the EU Large Combustion Plants Directive (LCPD) and Industrial Emissions Directive (IED). Gas/CHP generation capacity increases overall over the full period (6.3 GW). Nuclear capacity increases by a total of approximately 5 GW over the period. Wind starts from some 5 GW of capacity in 2012 but reaches 25 GW by 2020 and 49 GW by 2032. Hydro (including biomass and marine) increases from almost 2 GW currently to some 5 GW over the full period to 2032. Instead, generation capacity of pumped storage is cut in 50 % over the period.

Slow Progression (SP). Developments in renewable and low carbon energy are relatively slow in comparison to Gone Green and Accelerated Growth, and the renewable energy target for 2020 is not met until sometime between 2020 and 2025. The carbon reduction target for 2020 is achieved but not the indicative target for 2030.

This scenario places less emphasis on renewable generation. As Fig. 3 shows, coal capacity declines consistently to some 4 GW by 2032. Instead, gas capacity increases even more than before (10 GW more by the end of the period). Nuclear capacity remains fairly static. Growth in wind capacity is considerably slower in this scenario in comparison to Gone Green (capacity increases five-fold, not nearly ten-fold as before). Other renewables excluding wind remain fairly static. Pumped storage evolves basically as before.

Accelerated Growth (AG). This scenario has more low carbon generation, including renewables, nuclear and CCS, coupled with greater energy efficiency measures and electrification of heat and transport. Renewable and carbon reduction targets are all met ahead of schedule.

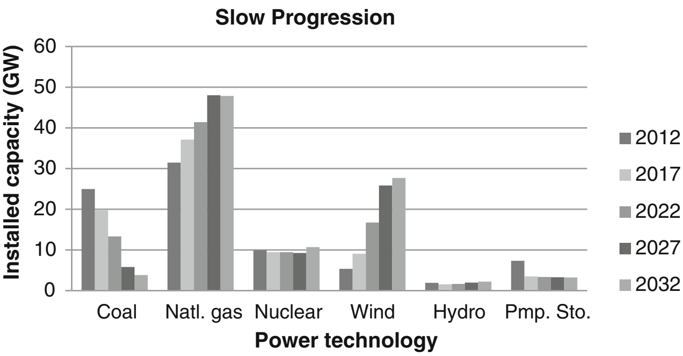

Fig. 3 Generation mix 2012–2032 under Slow Progression future energy scenario [29]

This scenario shows a much steeper increase in the level of renewable generation capacity than the others, as Fig. 4 shows. Coal capacity shows a net decrease over the period to 2032 of approximately 12 GW, with a slight U-turn at the end combined with CCS. Gas-fired capacity shows a mild increase over the period. Nuclear generation decreases a bit initially and then increases with the introduction of new nuclear plant. Wind generation capacity increases 12-fold in this scenario. Hydro capacity (alongside marine and biomass) also increases steeply over the period to 2032. Pumped storage evolves basically the same way as before.

Contracted Background (CB). This refers to all generation projects that have a signed connection agreement with National Grid. No assumptions are made about the likelihood of a project reaching completion. Assumptions regarding closures have only been made where there is an explicit notification of a reduction in Transmission Entry Capacity (TEC) or there is a known closure date driven by binding legislation such as the LCPD. The known LCPD closures entail a decrease in coal generation.

As Fig. 5 shows, this scenario has gas and nuclear generation capacities reaching their highest shares of the mix. There is also a large increase in contracted wind overall. Pumped storage falls short of the capacity levels assumed under Accelerated Growth.

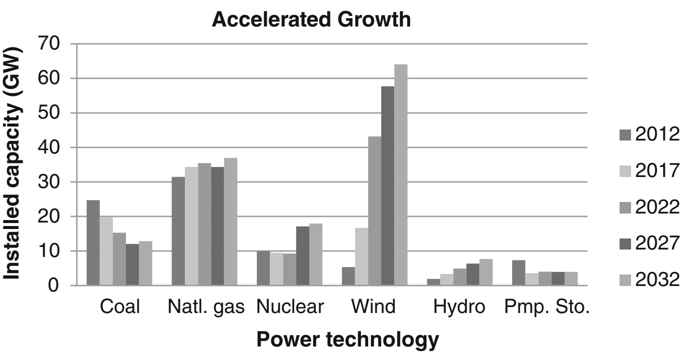

Fig. 4 Generation mix 2012–2032 under Accelerated Growth future energy scenario [29]

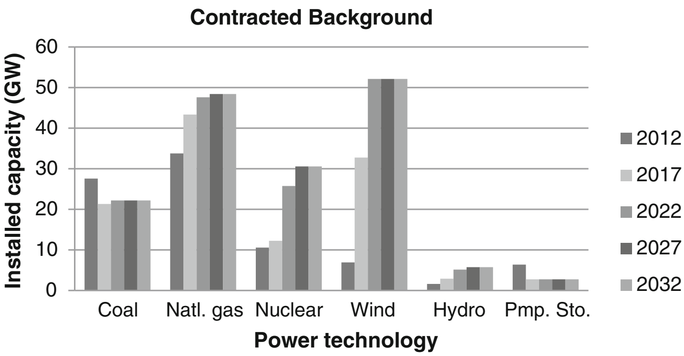

Fig. 5 Generation mix 2012–2032 according to the Contracted Background [29]

3.3 Carbon Price: Assumptions

Taxes on activities that have negative environmental impacts are an important component of both the tax system and the UK's environmental policies [17]. The climate change levy (CCL) is an environmental tax on electricity, gas, solid fuels and liquefied petroleum gas supplied to businesses and the public sector. It encourages energy efficiency to help the UK meet targets for cutting greenhouse gases, including CO_2 emissions. Transport taxes such as fuel duty, instead, are designed primarily to raise revenues for public expenditure.

The UK Government has introduced a carbon price support mechanism to support investment in low-carbon generation. From 1 April 2013 supplies of fossil fuels used in most forms of electricity generation are liable either to CCL or fuel duty. Supplies are charged at the relevant carbon price support rate, depending on the type of the fossil fuel used. The rate is determined by the average carbon content of each fossil fuel. The carbon price support rates for 2013–2014 represent the difference between the Government's target carbon price (the floor) and the futures market price for carbon in the EU ETS in 2013. These tax rates are equivalent to 4.94 £/tCO2 in 2013–2014 [18].

The carbon price floor announced in Budget 2011 begins at around 16 £/tCO2 in 2013 and follows a straight line trajectory to 30 £/tCO2 in 2020, rising to 70 £/tCO2 in 2030 (2009 prices). The floor will increase at around 2 £/tCO2 per year from 2013 to 2020. The floor effectively eliminates the lower part of a number of random paths of the carbon price. This policy measure (as compared to an unconstrained carbon price) has a double effect: it increases the average carbon price while decreasing its volatility. It in turn affects power technologies in different ways. The model handles this floor.

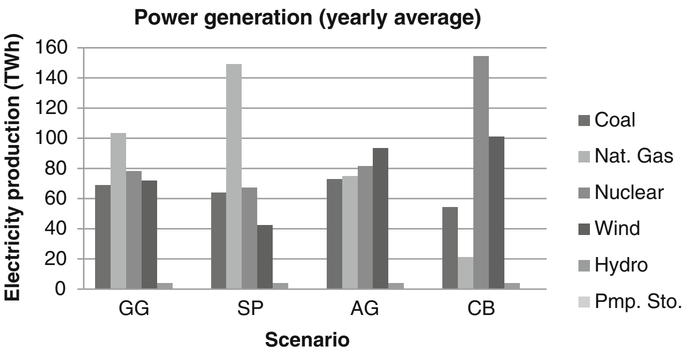

Fig. 6 Yearly average production by power technology under each scenario

3.4 Power Generation

Investments in power generation face a broad set of risks which affect competing technologies differently. The model solves for the generation level of several technologies and the amount of power served in each period. Hence it is possible to compute the cumulative power produced, and also a number of statistics of the underlying distribution. Figure 6 displays the role played by each technology on average under each scenario.

Figure 6 suggests that the AG portfolio delivers the most even levels of power generation in terms of the major technologies. CB has the most uneven portfolio from this viewpoint. Other renewables (hydro, biomass, …) and non-renewables (pumped storage, oil) play a minor role in any case.

Combined cycle gas turbines are set to become the major producers in the SP generating portfolio (less so in the GG portfolio). This is consistent with the relatively low development of renewable and low-carbon energy and the delay in meeting the environmental target. However, this situation is in sharp contrast with that in the CB portfolio. Indeed, it is here where gas-based generation reaches its minimum. Instead, nuclear stations appear as the major providers in the CB scenario.

We can relate these production levels to their respective capacities installed. This sheds light on the effective load factor of each technology which in turn affects their profitability.[11] Figures 7, 8, 9 and 10 show the results under each scenario.

Under the three future energy scenarios coal has a higher share in power generation than in capacity installed; however both shares are almost equal in the CB

[11] In models where optimal dispatch takes place on an hourly basis the underlying model is able to determine the effective number of operating hours (*ENOH*). The load factor equals *ENOH*/ 8,760. For instance the model in Delarue et al. [12] determines technology specific load factors by optimization. In our case, such a direct calculation cannot be made. Instead, we can calculate the effective electricity output from each technology in a given period and the maximum possible output in that period. Dividing the former by the latter we could get an indirect measure of technology specific load factors similarly by optimization.

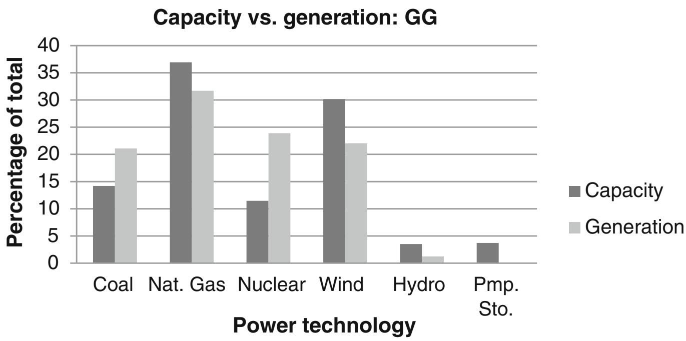

Fig. 7 Installed capacity relative to power production by technology under GG

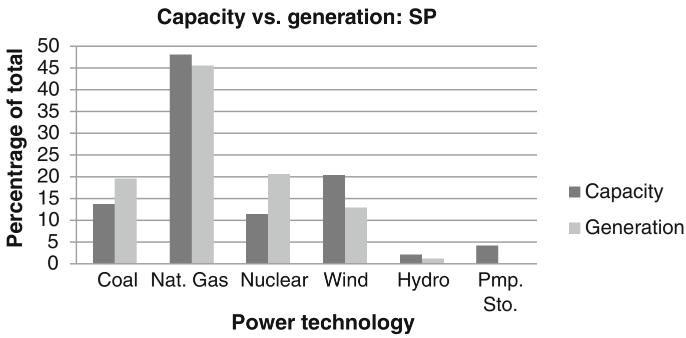

Fig. 8 Installed capacity relative to power production by technology under SP

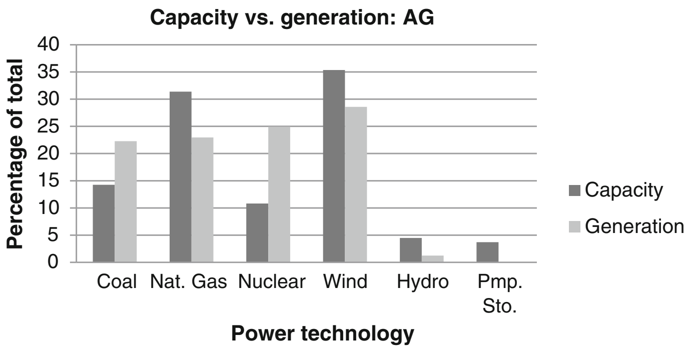

Fig. 9 Installed capacity relative to power production by technology under AG

portfolio. The situation is the opposite regarding gas-fired power plants. This suggests they fall short of running at anything close to full capacity. The difference is sizeable in AG, and particularly acute in CB; in this latter portfolio, there is room for concerns about their prospective profitability. Similarly to coal, nuclear always

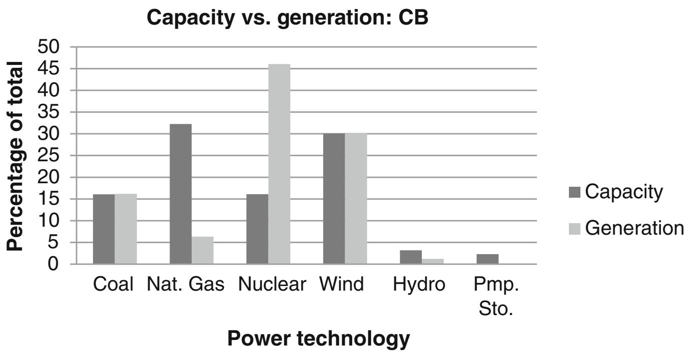

Fig. 10 Installed capacity relative to power production by technology under CB

reaches a higher share in terms of power delivered than installed capacity. The gap is most pronounced in the CB scenario. As for wind, the gap remains basically steady in all the portfolios other than CB, around seven percentage points. In the CB portfolio, the gap is almost zero with generation reaching its maximum share (30 %).

3.5 The Results in a Mean-Variance Context

It is well known that the various generation technologies display different risk-return profiles. Since each scenario puts a different emphasis on the competing technologies, the scenarios themselves show different risk-return profiles despite sharing a common demand pattern.

As already mentioned, the model minimizes costs by solving a dispatch problem one period after another. Each period the model determines an electricity price at which supply meets demand (this price is set by the marginal technology to enter the pool).[12] Thus there are as many electricity prices as periods or optimization problems. First these prices are discounted so as to get their present-value equivalents. Then we calculate the average or expected value alongside the standard deviation. Figure 11 displays the results under each scenario.

As Fig. 11 shows, GG and SP turn out to be almost indistinguishable from each other in terms of both average electricity price (€/MWh) and price risk.[13] They perform slightly worse than the AG scenario. The best performer is CB since it lies furthest to the left and to the south. Prices in this setting are so low because of the high share of zero-cost technologies entering the pool. Now, would nuclear plants

[12] These prices can be substantially lower than actual prices under market power [22].

[13] This overlap is by no means new in the related literature. Even radically different mixes can have nearly identical risk-return characteristics. As Awerbuch and Yang [5] put it: “There are many ways to combine ingredients to produce a given quantity of salad at a given price”.

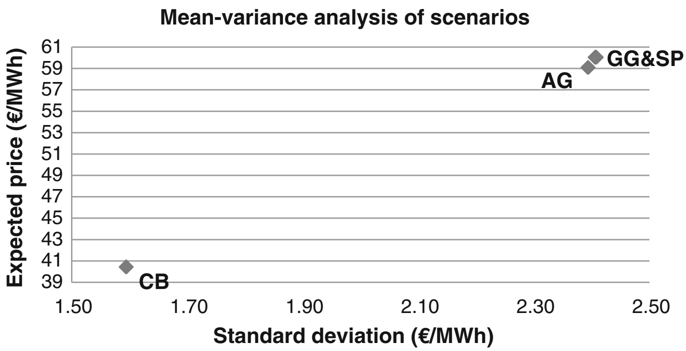

Fig. 11 Mean electricity price and volatility of GB generation portfolios over 2012–2032

be profitable at such low prices?[14] Would utilities change the way they bid in the power market?

Each of the 750 simulations delivers whole paths of a number of variables. For example, we have 750 levels of the electricity price from 2013 to 2032. Figure 12 shows the frequency distributions under each of the generation portfolios as envisaged in ETYS 2012. Most cases (and the probability mass) are concentrated around the average price. But they are skewed right: the electricity price becomes very high in a few cases.

It is possible to derive an average electricity price as a by-product of the model: in each optimization the operating technology with the highest cost sets the marginal price. So there are as many electricity prices as optimization problems. Each portfolio delivers an average price.

Following de Neufville and Scholtes [13], we examine the cumulative distribution functions (or CDFs, sometimes referred to as "target curves"), which present a lot of information in a compact form and thus provide an effective way to compare alternative generation portfolios; see Fig. 13. The target curve under the CB stays always above those of the other portfolios, that is, it stochastically dominates them. Thus the CB portfolio entails a lower probability of surpassing any given level of electricity price (the vertical distance from the target curve to 1.00).

3.6 Environmental Goals: Carbon Emissions

Needless to say, from a social planner's perspective the generating cost is the relevant measure [4, 6]. In a carbon constrained environment, this cost reflects the

[14] Lynch et al. [24] calculate (hourly) electricity prices from the (hourly) marginal cost of electricity provision and determine the return of each power technology under least-cost dispatch and marginal-cost pricing.

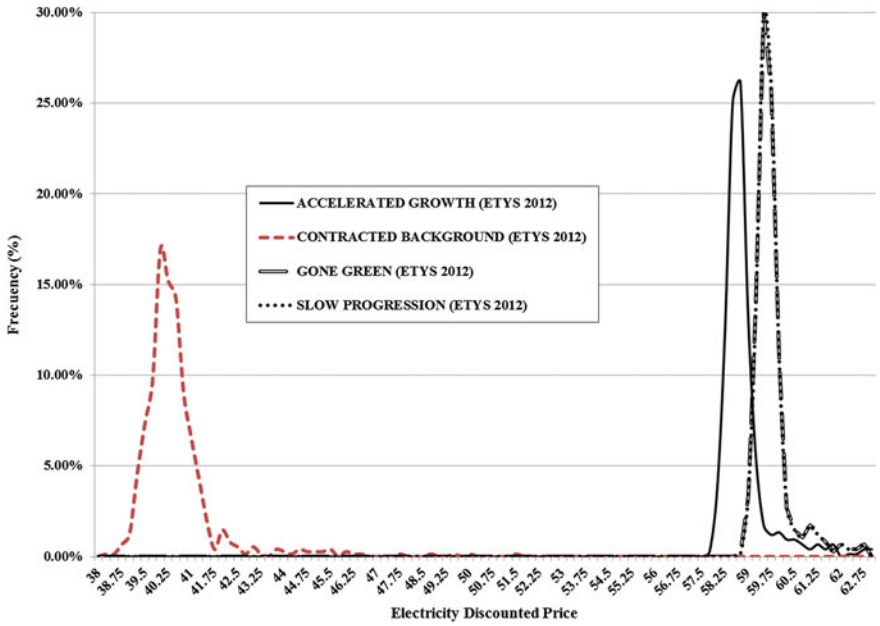

Fig. 12 Probability distribution of the average electricity price for different GB generation mixes over 2012–2032

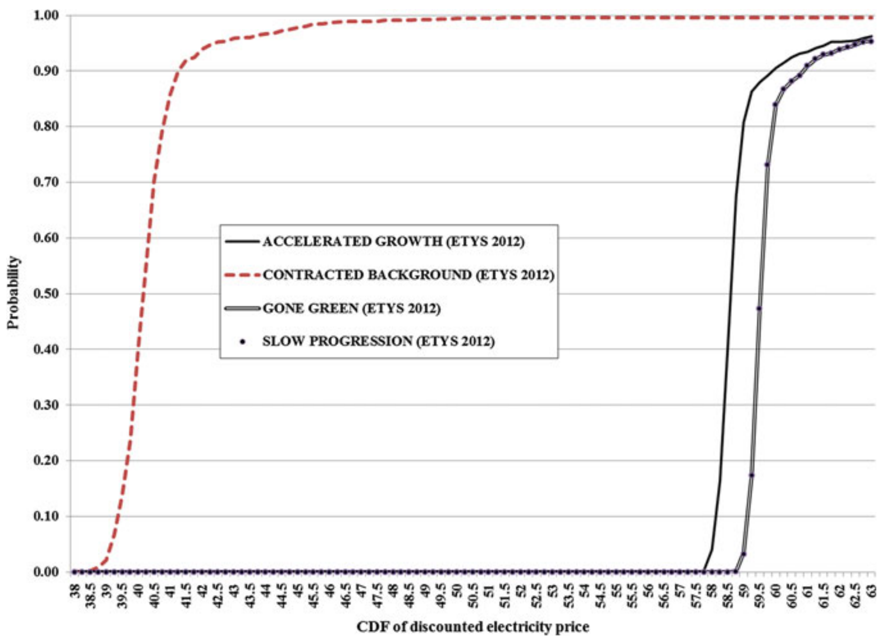

Fig. 13 Cumulative density function or "target curve" of the average electricity price for different GB generation mixes over 2012–2032

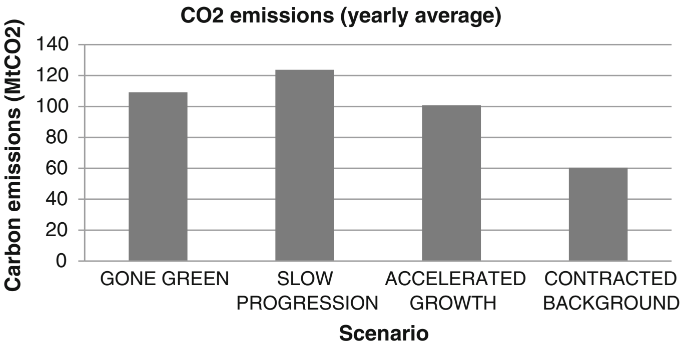

Fig. 14 Yearly average carbon emissions from each GB generation mix over 2012–2032

emission allowance price to some extent. Yet the amount of carbon emissions can be used as such to assess the four generation portfolios from an environmental point of view.

We computed the average of the 750 cumulative values for the above variables and others. Dividing these by the 20 years in our time horizon we obtained yearly averages.

Each scenario involves different utilization patterns of power technologies thus giving rise to different levels of CO_2 emissions. Here again the CB scenario outperforms the others, so in principle there seems to be no trade-off between cost efficiency and carbon objectives. Figure 14 displays the average results. Note that even if the time profile of these emissions is asymmetric (which will render average values unreliable), from an environmental viewpoint it is basically the same whether a ton of CO_2 is emitted in 2017 or 2023 (it will stay in the atmosphere for centuries). It is the cumulative emissions from each portfolio that matters. Since the time horizon considered is the same across the four portfolios, the ranking based on cumulative emissions coincides with that based on average yearly emissions.

Nonetheless, the time profile of these emissions is quite asymmetric (as the composition of the generating fleets changes over time) so their yearly averages must be taken with caution. We resort again to the target curves that result from alternative power portfolios; see Fig. 15. The CB portfolio stochastically dominates the other portfolios. In other words, it entails a lower probability of surpassing any given level of carbon emissions. As expected, AG comes second, followed by GG; SP portfolio is last.

3.7 Diversification and Concentration Issues

Depending on the prevailing circumstances, an efficient generation portfolio could in principle concentrate on one or two technologies (and hence primary energy sources). For example, the lack of long-term financial instruments for managing

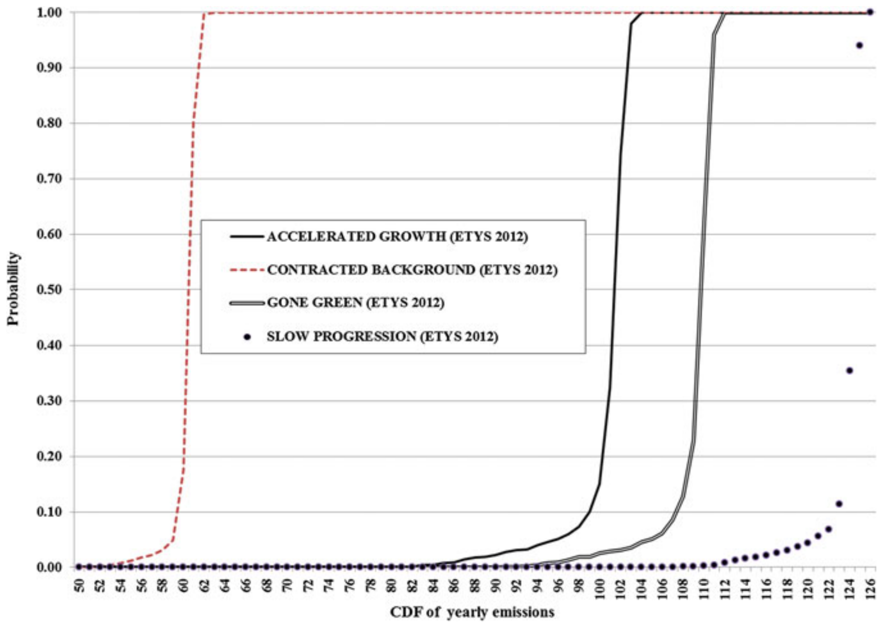

Fig. 15 Target curve of yearly average carbon emissions from different GB generation mixes over 2012–2032

risks may favor technologies that 'self-hedge' to some extent; Roques et al. [32]. This reliance on one or two pillars might jeopardize another policy goal, namely security of supply. Indeed, as these authors point out, actual electricity markets may not appropriately signal the need for diversity and flexibility at the macroeconomic level. In other words, there can be a trade-off between efficiency and security.

Further, MVP theory assumes that price shocks are stochastic. However, the fewer technologies a power system relies upon, the fewer (as a rule) the number of suppliers, and the more the system is exposed to the (non-stochastic) effects of collusion and monopoly; Krey and Zweifel [23]. This risk of collusion grows higher as the number of suppliers (or energy sources) becomes lower.

To depict a possible tradeoff between efficiency and security, we use several concentration indexes to quantify fuel mix diversity. Hill [19] identified and ordered an entire family of possible quantitative measures of diversity:

$$\Delta_a = \left[\sum_{i=1}^{I} p_i^a\right]^{\frac{1}{1-a}}, a \neq 1,$$

where Δ_a specifies a particular index of diversity, p_i represents (in economic terms) the relative share of option i in the portfolio under scrutiny, and a is a parameter that inversely measures the relative sensitivity of the resulting index to the presence of lower contributing options.

For $a = 1$, the above general form reduces to the so-called Shannon-Wiener diversity index:

$$\mathrm{SW} = \sum_{i=1}^{I} -p_i \ln(p_i).$$

The higher the SW index, the more diverse the system. If SW < 1, the system is highly concentrated and therefore subject to the risk of collusion or monopoly, leading to interrupted supply and/or price hikes [23].

For $a = 2$, the reciprocal of the resulting expression is the Herfindahl-Hirschman concentration index:

$$\mathrm{HH} = \sum_{i=1}^{I} p_i^2.$$

The HH index can range from 0 (full diversification) to 10,000 (total concentration). A value HH < 1,000 is taken by antitrust authorities as indicating no concentration. A value of HH > 1,800 has been interpreted as problematic in terms of exposure to supply risk.

Krey and Zweifel [23] apply these two indexes to U.S. and Swiss data to determine the trade-off between economic efficiency and security of supply. As they point out, "both [SW and HH] indices permit evaluation of the security of supply of different power generating technologies thanks to a greater number of suppliers. They therefore complement the MVP approach for policy makers who fear purchases of primary energy to be exposed to collusion or monopoly—a consideration of relevance especially in the markets for natural gas and uranium". Both indices help to determine whether a power generation portfolio is sufficiently diversified in terms of technologies (this in turn implies diversification in terms of purchases of primary energy sources).

We first looked at the initial capacities and those at the end of the time horizon under each scenario. Table 2 shows that the SW index is always higher than 1; below this threshold the risk of collusion looms. Relative to 2012, the SP portfolio points to a reduction of diversity; the opposite happens with the CB portfolio: it is the most diversified one. The HH index instead suggests that the SP portfolio is the least concentrated while CB is the most so.

It may be of interest to apply the SW and HH indexes not only to installed capacities but to generation levels as well. One or two scenarios suggest that some

Table 2 Diversity and concentration indexes of GB installed capacity from 2012 to 2032

	Installed capacity (2012)	Gone green (2032)	Slow progression (2032)	Accelerated growth (2032)	Contracted background (2032)
SW	1.455	1.440	1.281	1.441	1.500
HH	4,161	4,096	3,464	4,004	4,556

Table 3 Diversity and concentration indexes of GB installed capacity from 2012 to 2032

Index	Gone Green	Slow progression	Accelerated growth	Contracted background
SW: Capacity	1.494	1.412	1.510	1.511
SW: Generation	1.422	1.322	1.431	1.242
HH: Capacity	2,634	3,070	2,588	2,477
HH: Generation	2,508	3,057	2,463	3,336

power technologies will show load factors lower than usual. Table 3 displays the results (based on yearly averages of installed capacities and generation levels).

The SW index surpasses the threshold 1.0 which suggests that the underlying generation portfolio (and hence primary energy sources) is reasonably diversified. A higher SW index means a more diverse system. As before, CB happens to be the most diversified scenario in terms of average capacity while SP scenario is the least so. However, in terms of average production the AG portfolio is the most diversified whereas CB is the least diversified.

The HH index takes on values higher than 1,800 which implies that all generation portfolios are concentrated. Now, a higher HH means a system further away from perfect competition. The CB portfolio is the least concentrated in terms of installed capacity. Conversely, it is the most concentrated portfolio in terms of power generation; more competition among suppliers of primary energy would thus be particularly beneficial. In all, the preeminence of CB portfolio according to MVP analysis comes at a price in terms of the lowest diversification and highest concentration regarding power generation. On the other hand, note that GG and SP overlap in the MVP figure but this is not the case when it comes to the diversity index or the concentration index.

3.8 Sensitivity Analysis: Portfolio Performance Without a Floor Carbon Price

This section shows similar figures as before, under the alternative assumption of an unconstrained carbon allowance price. The standard assumption in the literature is that carbon price follows a GBM, which is a non-stationary process (thus adding significantly to price risk). Figure 16 displays the results under each scenario.

First, comparison with Fig. 11 shows that the average electricity price decreases while the standard deviation increases significantly in the absence of the carbon price floor. The previously overlapping GG and SP portfolios no longer overlap, yet they continue to be close to each other. They do not perform as well as the scenario AG in terms of expected price, but they are relatively less risky. The clear winner again is CB since it lies furthest to the left and to the south.

Regarding carbon emissions, not surprisingly they are higher now than in Fig. 14, since carbon prices can fall more when there is no support; see Fig. 17.

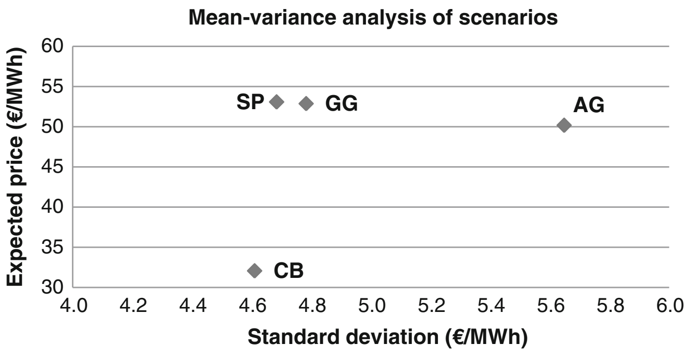

Fig. 16 Mean electricity price and volatility of GB generation portfolios over 2012–2032 without a floor carbon price

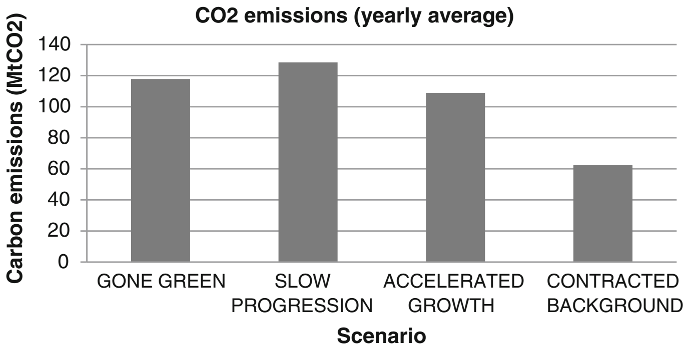

Fig. 17 Yearly average carbon emissions from each GB generation mix over 2012–2032 without a floor carbon price

Considering each portfolio in isolation, yearly average carbon emissions under GG rise by 8.7 $MtCO_2$, those under SP by 4.7 $MtCO_2$, those under AG by 8.1 $MtCO_2$, and finally those under CB by 2.1 $MtCO_2$.

4 Conclusions

MVP analysis has been increasingly adopted over the last decades to assess the performance of power generating portfolios in a number of countries. This is consistent with the notion that, in liberalized electricity markets, investors and utilities are concerned not only with the average or expected return on their investments but also with their risk. This basic tradeoff is suitably represented in a diagram with a measure of performance on the vertical axis (e.g. expected electricity cost or power per monetary unit) and a measure of risk on the horizontal axis (e.g. the standard deviation of the variable involved).

The traditional framework applies to a generating portfolio that is typically kept constant over the evaluation horizon (say, 20 years). It can be the current portfolio in a given country, or a target portfolio assumed to be in place sometime in the future.

Here we consider a generating portfolio in a dynamic context. We recognize the fact that the fleet of power plants changes over time as new stations connect to the electric grid and older ones cease operation. Further, we evaluate the performance of several generating portfolios in face of a common stochastic path of future demand. There is more to these real facilities than to financial assets, so other metrics beyond expected price and price volatility can be of interest too. Indeed, investors, utilities and policy makers aim at different goals, so the most relevant variables can differ among them.

We develop a valuation model that rests on cost minimization. Our measure of cost naturally includes that of power generation and of unserved load. Regarding the former, power producers under the EU ETS face both stochastic fuel prices and carbon allowance prices. As for the latter, in our model lost load has a non-negligible cost.

Uncertainty in our model extends beyond economic variables. It affects the state of physical infrastructures and/or their output. In sum, we deal with a problem of stochastic optimal control.

At any time, the optimization algorithm provides the level of power generation by technology, served load, aggregate generation costs, carbon emissions, and allowance costs, among other variables. The optimization model is nested in Monte Carlo simulation. A single run determines a number of state variables over $60 \times 20 = 1,200$ consecutive time steps. Under each setting, the optimization problem is solved. Therefore, one simulation run involves 1,200 optimizations. We repeat the sampling procedure 750 times. We thus come up with 750 time profiles of each variable of interest. In particular, our model can assess the performance of a pre-specified generation fleet in terms of the resulting expected price and the standard deviation around that expectation. When several generating portfolios are considered, comparing their relative performance sheds light on their respective advantages and weaknesses.

We illustrate the model by example. Specifically, we look at the British power generation mix over the time horizon 2012–2032. The 2012 Electricity 10 Year Statement envisages three future energy scenarios alongside the contracted background. Under Gone Green, the renewable target for 2020 and the emissions targets for 2020 and 2030 are all met. Under Slow Progression, instead, the 2020 target is not met until between 2020 and 2025; and the 2030 target is not achieved. Under Accelerated Growth renewable and carbon reduction targets are all met ahead of schedule. The Contracted Background portfolio refers to all projects that have a signed connection agreement with National Grid; reductions and closures with an explicit notification or date are also taken into account. Note that, as of 1 April 2013, the UK Government introduced a carbon price support mechanism. It aims at a carbon price floor around 16 £/tCO2 in 2013, 30 £/tCO2 in 2020, and 70 £/tCO2 in 2030 (2009 prices).

Regarding power generation in absolute terms, in the SP and GG portfolios gas turbines are set to be the major producers. However, they only play a minor role in the CB. In the latter, nuclear plants appear as the major providers.

The shares of coal and nuclear in power generation are higher than their shares in installed capacity under the three future energy scenarios. The opposite is true for gas-fired power plants. As for wind, its share of generation falls below that of capacity in all cases except CB, where they are at par (around 30 %).

In the MVP framework we looked at the average electricity price and standard volatility that result from each long-term power portfolio. GG and SP are almost indistinguishable from each other, and AG is very close. CB clearly outperforms all of them on both accounts, whether we focus on the typical scatter diagram or the more informative target curves. On the other hand, carbon emissions can be used to assess the performance of the above portfolios from an environmental viewpoint. Again, the CB portfolio outperforms the others by a wide margin.

Economic efficiency can lead us to rely heavily on a low number of technologies. This can jeopardize security of supply. Further, it can also give rise to anti-competitive practices or market power. We address these concerns by means of the Shannon-Wiener diversity index and the Herfindahl-Hirschman concentration index. When applied to yearly averages of installed capacity and power delivered, the four portfolios as of 2032 are reasonably diversified. CB in particular is the most diversified regarding capacity but the least so regarding production. At the same time, the four portfolios are problematic in terms of exposure to supply risk. CB is the least concentrated regarding capacity and the most concentrated regarding production.

We perform a sensitivity analysis with respect to the carbon price floor. In its absence, carbon price is assumed to evolve according to a standard GBM. As could be expected, the average electricity price is both lower and less volatile in the four portfolios. Again, CB is the clear winner. On the other hand, it is no surprise that carbon emissions are higher now that carbon prices can fall lower. The CB portfolio outperforms the other three also on this ground.

Our model can be improved in several ways. One involves better characterizing the strategic behavior of generators and the exercise of market power. Our model does not address strategic investment decisions such as how much generation capacity to add, and when to add it. These sequential investment decisions call for further research.

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[15] http://www.lowcarbonprogramme.org.

Appendix: Estimation

Load. Sample period: 2002:01–2013:08, i.e. a total of 140 monthly observations for GB. Tables A.1 and A.2.

Table A.1 OLS estimates of load seasonality

	Coefficient	*t-ratio*	*Coef. Adj.*
d(1)	3.43684	22.0155	*3.7462*
d(2)	1.59612	10.2244	*1.7398*
d(3)	3.37581	21.6246	*3.6796*
d(4)	−1.47726	−9.4630	*−1.6102*
d(5)	−2.11448	−13.5449	*−2.3048*
d(6)	−2.2726	−14.5577	*−2.4771*
d(7)	−2.83468	−18.1583	−3.0898
d(8)	−2.73487	−17.5189	−2.9810
d(9)	−2.27469	−13.9508	−2.4794
d(10)	0.254252	1.5593	0.2771
d(11)	1.47866	9.0687	1.6117
d(12)	3.69348	22.6523	4.0259

NoteCoef. Adj. stands for seasonal estimates of load plus transmission losses

Table A.2 Regression analysis statistics

Mean-dependent var	−0.011663	S.D.-dependent var	2.553337
Sum squared resid	37.43261	S.E. of regression	0.540779
R-squared	0.958694	Adjusted R-squared	0.955145
F(12, 128)	247.5705	P-value(F)	2.43e-82
Log-likelihood	−106.3144	Akaike criterion	236.6288
Schwarz criterion	271.9285	Hannan-Quinn	250.9735
Rho	−0.232423	Durbin-Watson	2.416934

Average deseasonalised load over the last 24 sample months: 24.90418 TWh. With transmission losses included: 27.14556 TWh. Load volatility: 0.1801.

Wind load factor. Sample period: 2006:04–2010:12, a total of 52 monthly observations. Tables A.3 and A.4.

Table A.3 OLS estimates of wind load seasonality

	Coefficient	*t-ratio*
d(1)	8.74421	9.1273
d(2)	−2.06081	−2.1511
d(3)	6.25051	6.5244
d(4)	−4.19477	−4.8954
d(5)	−4.65959	−5.4378
d(6)	−11.3065	−13.1949
d(7)	−8.8292	−10.3039
d(8)	−3.88958	−4.5392
d(9)	1.45744	1.7009
d(10)	1.74116	2.0320
d(11)	12.4732	14.5565
d(12)	4.4757	5.2232

Table A.4 Regression analysis statistics

Mean-dependent var	−0.209207	S.D.-dependent var	7.129921
Sum squared resid	165.2062	S.E. of regression	1.916050
R-squared	0.941968	Adjusted R-squared	0.927782
F(11, 45)	66.40291	P-value(F)	4.57e-24
Log-likelihood	−111.2076	Akaike criterion	246.4151
Schwarz criterion	270.9317	Hannan-Quinn	255.9431
rho	0.238200	Durbin-Watson	1.473965

Average wind load factor: 0.27. Wind load volatility: 0.9088.

Pumped load factor. Sample period: 1998:01 to 2013:08, i.e. 188 monthly observations.

Hydro load factor. Sample period: 1998:01–2013:08, or 188 monthly observations. Tables A.5 and A.6.

Table A.5 OLS estimates of hydro load seasonality

	Coefficient	*t-ratio*
d(1)	0.161759	11.7014
d(2)	0.0811138	6.8087
d(3)	0.0757758	4.6115
d(4)	−0.027608	−6.1159
d(5)	−0.122501	−11.3235
d(6)	−0.185731	−10.8948
d(7)	−0.16752	−13.7335
d(8)	−0.12782	−8.8027
d(9)	−0.0529903	−4.6321
d(10)	0.05018	6.5314
d(11)	0.125938	16.4867
d(12)	0.163624	10.2220

Table A.6 Regression analysis statistics

Mean-dependent var	−0.003719	S.D.-dependent var	0.133179
Sum squared resid	0.469528	S.E. of regression	0.051651
R-squared	0.858549	Adjusted R-squared	0.849708
F(12, 176)	91.90841	P-value(F)	4.00e-69
Log-likelihood	296.5316	Akaike criterion	−569.0632
Schwarz criterion	−530.2259	Hannan-Quinn	−553.3278
Rho	0.384711	Durbin-Watson	1.229343

Average hydro load factor: 0.3432. Hydro load volatility: 1.1099.

Pumped load factor. Sample period: 1998:01–2013:08, i.e. 188 monthly observations Tables A.7 and A.8.

Table A.7 OLS estimates of pumped load seasonality

	Coefficient	*t-ratio*
d(1)	0.00150627	3.7567
d(2)	0.0012892	5.5566
d(3)	0.00827051	13.3275
d(4)	−0.0123687	−10.2670
d(5)	−0.00954283	−8.4641
d(6)	0.00018299	0.1880
d(7)	−0.00347042	−2.8817
d(8)	−0.000364568	−1.3049
d(9)	0.00139669	1.2297
d(10)	0.000694149	0.7116
d(11)	0.000860186	1.8030
d(12)	0.0118433	10.5627

Table A.8 Regression analysis statistics

Mean-dependent var	−0.000053	S.D.-dependent var	0.007214
Sum squared resid	0.002323	S.E. of regression	0.003633
R-squared	0.761330	Adjusted R-squared	0.746413
F(12, 176)	62.45414	P-value(F)	6.75e-57
Log-likelihood	795.5788	Akaike criterion	−1567.158
Schwarz criterion	−1528.320	Hannan-Quinn	−1551.422
Rho	−0.152526	Durbin-Watson	2.304938

Average pumped load factor: −0.0845. Pumped load volatility: 0.4660.

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