Is Renewable Energy a cost-effective mitigation resource?

An application to the Spanish electricity market

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Abstract: This paper evaluates the net effect of renewable energy policy in Spain from 2002 to 2015 and calculates its cost-effectiveness in terms of CO_2 emission reductions in the production of electricity. Our conclusions indicate that although the phasing out of Feed-in Tariffs reduced the regulatory costs, it also limited renewable participation in the electricity market, leading to an increased electricity price and higher emissions. According to our results, the joint effect of *(i)* the value of avoided emissions due to renewable energy participation and *(ii)* the merit order effect was able to compensate for the regulatory costs (subsidies) up until 2010, while the sign of the net effect was reversed from 2011 to 2015. Finally, we find that the economic implications of emission reductions are highly dependent on how the social cost of carbon is measured.

Keywords: Energy Policy, Renewable Energy, Feed-in Tariffs, European Emission Trading System, Social Cost of Carbon, Climate Change.

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1. Introduction

The international community recognizes climate change as one of the most important risks for humanity and encourages efforts to limit global temperature rise to 2 degrees Celsius above pre-industrial levels (IPCC, 2014). Greenhouse gas (GHG, hereafter) emissions have proven to be directly linked to global warming and breaking current emission trends (i.e. mitigation) in the short term is thus key to ensuring temperature stabilization (Friedlingstein et al., 2014). In this context, the role of the energy sector becomes crucial for the climate change mitigation process. In fact, the source of 65% of worldwide emissions is the use of energy (through fossil fuel combustion) and around 40% of the global electricity supply derives from coal-fired stations, the top air pollutant source in the power sector (IEA, 2016). Some of the behavioural changes needed to mitigate this problem include measures such as shifting towards lower-emitting fuels, increasing energy efficiency -both in generation and demand-, reducing deforestation and pursuing the carbon capture and storage technologies (Arrow, 2007). Therefore, given their non-emitting and non-depletable nature, Renewable Energy Sources (RES, hereafter) represent an important element in the transition towards a low carbon economy.

In particular, the Electricity from RES (RES-E, hereafter) has been developed in many countries thanks to government support, justified by its positive socioeconomic and environmental impacts, with the cost of subsidies generally transferred to electricity consumers. In this paper, we perform a regulatory impact assessment by analyzing the *net social cost* (or benefit) of Renewable Energy (RE, hereafter) promotion, and considering not only the economic but also the environmental effects of RES-E. To compute the net social cost, we first calculate the net effect of RES-E regulation on the monetary costs for consumers (*net monetary cost*), considering that they pay the market price for electricity and also the incentives to green energy, which are included in the bill. Second, we evaluate the environmental benefit of avoided emissions and add up the result to the monetary cost to obtain the net social cost of RES promotion.

The application to RES in Spain is of special interest, given that Spain is one of the leading countries in RES promotion worldwide; according to the International Energy Agency, the share of solar in total primary energy supply[1] is the highest among the International Energy Agency countries, while the wind share is the third-highest behind Denmark and Portugal (IEA, 2015). Additionally, the important growth of RES-E in Spain has been supported by a combined system of Feed in Tariffs (FIT, hereafter) and Premiums (FIP, hereafter) from 2008 to 2012 and accompanied by an important increase in the regulatory cost of the electricity system. This FIT-FIP system was phased out in the electricity reform passed in 2013, in an attempt to tackle the growing deficit of the electricity system. For the period prior to the reform, 2008-2012, Ciarreta, Espinosa and Pizarro-Irizar (2014) obtained the net monetary costs of RES promotion, but no consideration was given to its environmental benefits. Finally, Spain/the Iberian peninsula is (close to) an energy island (i.e. there are very few interconnections with some other countries and, as a consequence, imports/exports are limited), a fact that makes the Spanish case sort of interesting for the proposed research study.

Concerning the environmental effects, RE reduces the use of conventional sources (i.e. coal, oil or natural gas), since it acts as a substitute for fossil technologies in electricity production. This helps to mitigate the GHG emissions produced in the electricity sector, which is responsible for 28% of carbon dioxide (CO_2, hereafter) emissions in Spain, only surpassed by the transport sector with 34% (IEA, 2015). We assess the economic benefits derived from the substitution of conventional sources by converting those emission reductions into monetary terms. We follow two different approaches to perform this environmental impact assessment: *(i)* a market-based approach, based on the actual price of the EU's Emission Trading System (EU ETS, hereafter); and *(ii)* the Social Cost of Carbon (SCC, hereafter) approach based on the marginal cost of emitting one extra ton of CO_2. If SCC estimates and market emission allowances were perfect signals, both approaches would be equivalent. However, this is not the case and annual average prices for emissions allowances in Europe, for instance, were even below the lowest SCC mean value in 2013.[2] Therefore, since carbon markets are not efficient, a carbon value that takes social costs into account needs to be constructed. In fact, SCC estimates are hotly debated in the literature, and surely will remain so in the foreseeable future (for instance, two polar examples can be found in Revesz et al., 2017 and in EPA, 2017), which makes this research interesting from a policy perspective.

The goal of our paper is twofold. First, we assess the net cost of the RES-E deployment in the Spanish electricity system in a timeframe (2002-2015) that allows us to analyze the market when renewable participation was still low (2002-2007), when renewable greatest expansion took place (2008-2012) and the effect of the phasing out of the incentive system from 2012 onwards. Second, we quantify the environmental impact derived from the displacement of conventional sources of energy by RES-E. The avoided emissions assessment is carried out by comparing market and SCC approaches, including emissions from both CO_2 and other air pollutants (nitrous oxide-NO_x, sulfur dioxide-SO_2 and particulate matter-PM).[3] The results are relevant to the debate over the financial burden of the RES-E implementation and the discussion about the instruments and mechanisms for climate change mitigation at the lowest cost.

The rest of the paper is structured as follows. Section 2 reviews previous literature regarding the effect of RES-E deployment and carbon prices. Section 3 then describes the data and the methods applied, and Section 4 discusses the main results. Finally, Section 5 presents the conclusions and policy implications.

2. Beyond the merit order effect

The presence of RES-E in power markets affects the two components of the market price in different ways: *(i)* the regulated component, which increases prices due to the payment of the FITs by the electricity consumers; and *(ii)* the market component, which modifies prices due to the presence of the RES-E in the energy mix. This latter effect is known as the merit order effect (MOE) and the combination of these two opposite forces determines the net effect of RES-E on consumer prices.

The MOE is one of the most studied phenomena regarding the deployment of RES-E. From a theoretical standpoint, Jensen and Skytte (2002, 2003) were among the first to point out that the integration of RES-E into the generation mix reduces the electricity market price. This is due to its lower variable costs compared to conventional fuel electricity sources. Since RES-E uses inputs that cannot be accumulated (e.g. wind or sun), the opportunity cost for non-dispatchable energy sources is zero. Consequently, RES-E producers, unlike conventional fuel generators, have the incentive to sell the electricity generated at zero prices, displacing conventional fuel electricity sources and reducing the market electricity price (Gallego-Castillo and Victoria, 2015). Additionally, when the MOE is computed as the difference between actual electricity prices and counterfactual prices in absence of RES-E (*ceteris paribus*), it also controls for other factors that could be affecting prices, such as demand changes, supply changes, fossil fuel price changes and carbon price changes. It could be argued that without incentives to renewable energy, investors would have launched other projects in different technologies. However, this is unlikely for Spain, given that the electricity market exhibits high reserve margins even excluding renewable sources (Ciarreta, Espinosa and Pizarro-Irizar, 2014). Another criticism to this methodology could be that other technologies' supply curves could be affected in the long run by RES-E presence (given the intermittency of some sources). Ciarreta, Espinosa and Pizarro-Irizar (2017) explored the shape of Spanish supply curves before and after the introduction of renewable sources and concluded that only combined cycle plants (11% of the electricity mix in 2015) experienced a change in the slope of their supply curves as a consequence of RES-E.

The MOE has been widely analyzed in the empirical literature for energy policy analysis. Sensfuß, Ragwitz, and Genoese (2008) and Sáenz de Miera, del Río González, and Vizcaíno (2008) were among the first authors conducting empirical analysis on this effect for Germany and Spain, respectively. Similarly, other authors have also focused on this approach: Weight (2009) and Cludius et al. (2014) for Germany; Munksgaard and Morthorst (2008) for Denmark; Forrest and MacGill (2013) and Cutler et al. (2011) for Australia; and, Gelabert, Labandeira, and Linares (2011), Gil, Gomez-Quiles, and Riquelme (2012), Azofra et al. (2014) and Ciarreta, Espinosa, and Pizarro-Irizar (2014) for Spain, among others.

However, when assessing the economic impact of RES-E, other environmental implications should also be taken into account. In this regard, the emission reduction due to RES-E has already been quantified in the empirical literature. For Europe,[4] van den Bergh, Delarue, and D'haeseleer (2013) showed that total annual CO_2 displacement due to RES-E deployment was over 100 $MtCO_2$/year for the period 2007-2010. According to Rathmann (2007), Germany was able to reduce CO_2 emissions by 25.7 $MtCO_2$/year from 2000-2002 to 2005-2007 due to the public support devoted to RES-E. For Spain, Ortega, del Río, and Montero (2013) calculated that the total avoided emissions for Spain during 2002-2011 ranged between 122.5 and 168.3 $MtCO_2$, peaking at 27.9 $MtCO_2$/year in 2011.

There are two main approaches to translate this RES abatement potential into economic terms. First, if emission allowance markets were efficient, actual market prices should provide the marginal cost/benefit of reducing emissions. However, actual market prices may not reflect the marginal costs and benefits of reducing emissions and usually they are highly volatile. Second, the approaches based on the SCC predict the potential future damage caused by emissions, although they involve a large uncertainty in the estimates.

Using historical carbon prices, and looking at renewable incentives only as a policy to abate CO_2 emissions, Marcantonini and Ellerman (2015) found that German support for wind energy induced reductions of CO_2 emissions at a carbon price higher but of the same order of magnitude than the historically observed EU ETS price, but incentives to solar power led to abatement costs above EUR500/tCO_2. The literature provides empirical evidence supporting the fact that RES deployment reduces emission prices (Koch et al. 2014). Specifically, Rathman (2007) suggests that current EU ETS prices are 27% lower due to RES-E participation. In this case, using carbon prices to evaluate mitigation could underestimate the potential abatement savings of RES (see Appendix A.1 for a detailed description of the policy framework in the EU, including the EU ETS and RES-E promotion instruments).

On the other hand, the approaches to SCC-based carbon valuation compute the net present value of the incremental damage due to a small increase in CO_2 emissions (i.e. the marginal damage cost of emissions). The SCC includes changes in agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services, among others

(Greenstone, Kopstis and Wolverton, 2013). From a policy perspective, the SCC would be equivalent to a Pigouvian tax levied on carbon (Tol, 2009). The aim of this approach is to express non-market impacts in monetary value for policy decision making; this translation is based on different assumptions: the rate at which the benefits (or costs) are discounted, the way in which uncertainty is treated, the selected projections of CO_2 emissions and the chosen estimates for the rate of global warming, among others (Tol, 2009). Different assumptions would result in different monetary values of the SCC, which increases the uncertainties of this method.[5] Tol (2005) evaluated 94 estimates from 28 published studies of marginal damage costs under different discount rates and showed that lower discount rates not only increase the SCC estimates, but also the uncertainty. According to this analysis, the combined mean estimate for marginal damage cost is \$16/tCO_2 for a 3% pure rate of time preference, not exceeding \$62/tCO_2 with a probability of 95%, and \$51/tCO_2 for a 1% discount rate. Given these values Tol (2005) claims that the marginal damage costs of carbon dioxide emissions are unlikely to exceed \$50/tCO_2. In a later study, Tol (2012) analyzed 232 SCC estimates, with mean values of EUR49/tCO_2, modal estimates of EUR14/tCO_2 and median of EUR32/tCO_2.

In addition to the theoretical literature, the SCC approach has already been used as a policy tool by the US Environmental Protection Agency. The US government established an Interagency Working Group (IWG, 2010) for developing SCC estimates. The purpose was to provide US agencies with an estimate for assessing the costs and benefits of an intended regulation. The quantitative SCC estimates come from three Integrated Assessment Models (DICE, FUND and PAGE)[6] and three discount rates were selected in order to capture the uncertainties involved in regulatory impact analysis (IWG, 2010). The 3% rate is used as the central estimate; it represents the after-tax risk-free rate of return and it is usually recommended for US government policy analysis (Ackerman and Stanton, 2012). The 5% rate (low estimate) represents the possibility that climate damages are positively correlated with market returns; and the 2.5% rate (high estimate) represents the negative correlation between the returns to climate mitigation and the economy's growth rate (Greenstone, Kopits and Wolverton, 2013). The SCC estimates also include a fourth scenario for the 95th percentile at a 3% discount rate, which represents the higher-than-expected impacts from temperature change that would occur at a lower probability and would be particularly harmful for society (IWG, 2010).

The first US estimates were presented in 2010, revised in 2013 and corrected in minor ways in 2015 (IWG, 2016).[7] These SCC estimates were determined at a global level rather than from a domestic perspective (which allows their use outside the US). First, because climate change is a global externality and, consequently, estimates should incorporate the global damages; and second, because one country alone (the US in this case) cannot solve the climate change problem (Greenstone, Kopits and Wolverton, 2013). Finally, these estimates do not weight damages by the income level in the region where they occur, which is one of the main sources of criticism of this methodology (together with the uncertainty that the selection of the discount rate imposes). Since the majority of climate impacts are expected to occur in low-income countries (Johnson and Hope, 2012), including equity weights would increase the SCC values.

In 2007, the UK likewise set an official shadow price (£25.5/tCO_2 in 2007, rising at an annual rate of 2% in real terms) for government policies based on SCC estimates (DECC, 2009). However, they shifted in 2009 to a target-consistent approach based on the EU ETS prices (to be consistent with the EU), although they continue to monitor the SCC. In fact, the EU trend is towards the use of carbon prices (EU ETS) in policy appraisal.

Table 1 shows some SCC estimates (mean, maximum and minimum values) for 2020 for the EU, UK and US. Despite the differences in methodology[8] (e.g. US estimates do not consider equity weighting, whereas UK estimates include it) and monetary units, all of them are of similar order of magnitude.

[Insert Table 1 here]

Barbose et al. (2016) applied the SCC values from IWG (2016) to assess the economic benefits of compliance with the Renewable Portfolio Standards in terms of reduced climate change damages in the US. The authors reported benefits from avoided future damages associated with new RES-E in 2013 of $2.2 billion for the central estimate, $0.7 billion for the low, $3.5 billion for the high and $6.3 billion for the higher-than-expected case. In the case of Spain, Ortega, del Río, and Montero (2013) used the SCC modal and median values determined by Tol (2012) for the monetary valuation of CO_2 emissions avoided by RES-E in the period 2002-2011, which ranged between EUR 1,714.4 and 5,385.9 million, depending on the scenario; Sanz et al. (2014) used the average carbon market price to provide an economic assessment of GHG savings associated with the use of biofuels for the transportation sector in Spain in 2010.

Finally, despite the fact that CO_2 is the most significant pollutant in climate and energy policy, given its impact on global climate change, other air emissions produced by conventional electricity generation also affect air quality conditions and are thus addressed at the local policy level (a reduction of these gases would induce health co-benefits, including avoided premature deaths and reduced morbidity). Similarly to the SCC approach for CO_2, Shindell (2015) applied the Social Cost of Atmospheric Release (SCAR) methodology for assessing the marginal cost of other air pollutants.

3. Methods and Data

This paper explores the net social cost of regulation and analyzes whether RES-E has been a cost-effective mitigation mechanism. To this end, we first use a market algorithm to quantify the MOE effect of RES-E (Section 3.1). Then, we add the regulatory costs (subsidies) and compute the net effect of RES-E on final prices for consumers, i.e. the net monetary cost (Section 3.2). Our algorithm also provides the amount of energy from conventional sources that is displaced by RES-E, which measures the mitigation potential of RES-E in energy terms. We evaluate the environmental benefits in monetary terms (to make them comparable to the economic costs) using two different approaches: emissions market prices (Section 3.3) and a social cost approach (Section 3.4). Finally, we compute the net social cost considering both the net monetary cost and the environmental benefits. Figure 1 presents the diagram that summarizes our numerical approach. Note that in our analysis we are not presenting the variation in total welfare, since we focus only on the consumer surplus (ignoring the producer surplus).

[Insert Figure 1 here]

3.1. Actual and Counterfactual Scenarios

We need to determine the effect of RES on the electricity market in order to assess the monetary costs. A three-equation algorithm allows us to compute the day-ahead market[9] hourly outcomes (see Appendix A.3 for a description of how this market operates). Equation (1) represents the fact that for each price p_i the quantity traded (q_{min}) coincides with the short side of the market, supply (q_{bid}) or demand (q_{ask}). Equation (2) computes the quantity traded (q) in one hour using the short side of the market in (1). Equation (3) identifies the market clearing price (p) for one hour.[10]

$$q_{min}(p_i) = \min\{q_{ask}(p_i), q_{bid}(p_i)\} \quad (1)$$

$$q = \max_{p_i}\{q_{min}(p_i)\} \quad (2)$$

$$p = \{q_{bid}^{-1}(q)\} \quad (3)$$

We need to introduce a set of equations, (4), one for each technology, to obtain the hourly electricity production for each technology at the market clearing prices. Subindex k stands for nuclear, coal, combined cycle, Special Regime (which includes RES-E and cogeneration), hydropower, and fuel or fuel-gas; $q_{bid\_k}(q)$ denotes the aggregate volume of matched bids from technology k at p_i or lower prices, so that $q = \sum_k q_k$.

$$q_k = q_{bid\_k}(q) \quad (4)$$

The algorithm returns hourly time series of market clearing prices and quantities traded by technology type. We compute market values under two scenarios: the actual and the counterfactual. The former represents actual equilibrium outcomes for each hour, while the latter is the counterfactual equilibrium resulting from the exclusion of RES-E. In the counterfactual scenario, the RES-E generation is removed from the supply curve, while leaving the remaining technologies and demand unchanged.

3.2. The net monetary cost of RES-E

The comparison between the actual and counterfactual scenarios allows us to quantify the net monetary cost of RES-E. The net monetary cost is computed as the difference between the costs and the savings entailed by RES-E. The costs in our analysis refer to the regulatory costs, *RC*, or subsidies (see Appendix A.2 for a description of the Spanish policy concerning the promotion of renewable sources in electricity generation), whereas the savings are related to the MOE and computed as the market cost difference between the counterfactual (P_C*Q_C) and the actual (P_A*Q_A) scenarios (*MOE*= P_C*Q_C - P_A*Q_A). Therefore, the net monetary cost (*NMC*) for consumers is *NMC*= *RC*-*MOE*, which would be positive if regulatory costs for renewable sources were higher than their market savings due to the MOE, or negative if RES entailed more savings than costs. We then divide the net monetary cost NMC by the amount of RES-E (Q_{RES}) and obtain the unit net monetary cost (*UNC*): *UNC*=*NMC*/Q_{RES}.

The data to calculate the net monetary cost of RES-E come, on the one hand, from the market prices and quantities derived by our algorithm, computed on information on the hourly price and quantity bids from the Spanish electricity market operator (OMIE)[11] (see OMIE, 2016). On the other hand, the National Commission of Markets and Competition (CNMC),[12] the Spanish electricity system regulator, provides data on public support of RES-E (see CNMC, 2015).

Finally, since electricity demand is subject to high daily and seasonal variations, we also assess the effect by considering the demand daily patterns. We split the results for the peak hours (high demand) and the off-peak hours (low demand).[13]

3.3. Environmental Perspective

In order to address the environmental effect, the net monetary cost is compared with the value of the avoided emissions resulted from renewable participation in the day-ahead market. The comparison between the net monetary cost and the benefit from avoided CO_2, SO_2, NO_x and PM emissions represents the impact of RES-E as a mitigation resource (the net social cost).

We first compute the amount of energy from conventional sources that is displaced by RES-E, where CC_D stands for the quantity displaced for combined cycle plants, CT_D for coal, FG_D for fuel-gas, HY_D for hydropower and NU_D for nuclear to calculate avoided emissions. Each of these variables is computed as the difference between the energy traded for each technology in the actual and counterfactual scenarios. For instance, $CC_D=Q_{CCA}-Q_{CCC}$, where Q_{CCA} is the amount of energy corresponding to combined cycle plants in the actual scenario and Q_{CCC} is the amount of combined cycle energy in the counterfactual scenario without RES-E.

Once we obtain the annual mitigation in energy terms (GWh) for each technology, we translate it into emission terms (tons of pollutant) multiplying the energy savings in GWh by the emission potential of each technology in t/GWh (CNMC, 2014). We perform it for the three emitting technologies: combined cycle, coal and fuel-gas; and for four different pollutants: CO_2, SO_2, NO_x and PM. CO_2 is the most significant for global warming in the long term (a long-lived gas). However other air pollutants such as SO_2, NO_x and PM also deserve attention, since they impact air quality (leading to adverse health effects) and worsen the environment (e.g. the acid rain affecting forests and water reservoirs).[14]

The CNMC (CNMC 2014) published yearly figures for CO_2, SO_2, NO_x and PM emissions in grams per kWh for combined cycle, coal and fuel-gas between 2001 and 2012; we assume that the emission potential of 2012 holds also for 2013, 2014 and 2015.

For the monetary valuation of the avoided emissions, we use two different approaches, i.e. the market approach (Section 3.3.1) and the social cost approach (Section 3.3.2), given that both of them may offer some advantages over the other. For instance, volatility in the emission allowances prices is large, but uncertainty levels on social cost estimates are also high (see Section 2 above).

3.3.1. Market Approach

Under the assumption that the market for emission allowances is optimally designed, the market price would reflect the value of environmental damages of an additional unit of pollutant. For CO_2 analysis we use the price of the EU ETS system for the period 2008-2015, which comprises Phases II and III (Sendeco2, 2016). However, for the remaining of pollutants, due to the lack of markets in Europe, we use 2008-2015 US Clean Air Market auction prices for SO_2 (EIA, 2012 and EPA, 2016) and during 2008-2011 for NO_x (EIA, 2012).[15] The RES-E mitigation potential is computed by multiplying the annual avoided emissions by the annual allowance price.

3.3.2. Social Cost Approach

Relaxing the assumption that the market price for emission allowances reflects the value of the environmental damages, another option is to estimate directly the social cost of the environmental damages using the SCC approach for CO_2 and the SCAR approach for SO_2 and NO_x.

We use US data (IWG, 2016) for the SCC approach, given that they contain SCC estimates for each year from 2010 until 2050 and are currently being used with policy purposes. Our analysis considers the period 2008-2015, so we compute the SCC estimates for 2008 and 2009 as a linear projection using the growth rate between the 2010 and 2015 estimates. Table 2 shows the SCC values in $/t$CO_2$ (2007-constant US dollars). The use of different discount rates provides lower and upper limits for our calculations. In order to convert the values into current euros, the reported price in dollars for each discount rate is divided by the annual exchange rate reported by the Spanish central bank (*Banco de España*, in short BDE) and multiplied by a GDP deflator retrieved from the US Bureau of Economic Analysis (BEA). The SCC estimates in current euros are then multiplied by the avoided emissions of CO_2. The result is the total value of the SCC in current euros.

[Insert Table 2 here]

For the SCAR approach we obtain the estimates using data from Shindell (2015), which are available only for the year 2010 and for the 5% and 3% discount rates, and IWG (2016). Shindell (2015) provides the valuation of a 1% reduction of 2010 anthropogenic emissions for CO_2, SO_2 and NO_x (among other pollutants). Observing the ratios CO_2 - SO_2 and CO_2 - NO_x, and using these ratios together with the SCC estimates from IWG (2016), we calculate SCAR estimates for SO_2 and NO_x (see Table 3).

[Insert Table 3 here]

4. Results and Discussion

Applying the methodology described in Section 3, we compute the effect of regulation on RES-E development and its economic burden on consumer prices (Section 4.1). Additionally, we analyze some of the environmental implications of RES-E deployment and we quantify them in economic terms following different approaches (Section 4.2). Finally, we combine the net monetary cost and the environmental benefits to report the net social cost (Section 4.3). If the regulatory costs of RES-E turned out to be lower than the environmental benefits, RES-E could be considered a cost-effective mechanism against climate change. In any case, RES-E produces other socio-economic benefits (employment, local industry deployment, security of supply, savings in imported fossil fuels, etc.) that are not considered in our analysis.

4.1. The net monetary cost

During the period 2002-2015, the market electricity prices dropped due to the MOE of RES-E. Figure 2 shows the annual average price difference (solid line) between the actual (PA) and counterfactual (PC) scenarios (PC-PA). Note that the price difference due to RES-E broadened after 2004, coinciding with the passing of the Spanish Renewable Energy Act. It increased by almost ten times in just two years (2004-2006), from 2.8 to 25 EUR/MWh, and this price gap peaked at almost 45 EUR/MWh in 2009. Despite the cuts to the FIT-FIP system since 2010, between 2006 and 2015 the price difference has never been below 24 EUR/MWh.

Figure 2 also shows persistence across peak and off-peak periods in the price reduction, although gaps are larger for the high demand hours (dashed) than for the low demand ones (dotted line) and mean price reductions (solid line) lay between them. This is due to the fact that RES displace more fossil electricity in high demand hours and, therefore, the MOE is larger.

[Insert Figure 2 here]

Although RES-E decreased electricity prices in the period 2002-2015, the growth of RES-E on the Spanish electricity market has been supported through an incentive system based on FIT and FIP, implying an increasing financial burden for the system. Figure 3 shows that the annual regulatory cost for RES-E (dashed line) rapidly increased as RES-E production (solid line) soared upward. In 2002, the regulatory cost represented EUR 13 million, and in just four years it exponentially rose to over EUR 1 billion in 2006. Between 2006 and 2008, the support scheme cost rose by almost EUR 1 billion per year. In addition, in just one year (2008-2009) the support cost shot up by almost EUR 3 billion. After 2009, the support cost continued to increase up until 2013 when it reached EUR 9 billion, its maximum level. Finally, the burden for 2014 and 2015 decreased by over EUR 1 million due to a lower RES-E participation in the pool after the electricity reform that phased out the FIT-FIP system in Spain.

[Insert Figure 3 here]

Figure 4 presents the unit net monetary cost of RES-E (solid line), computed as the difference between the market savings derived from RES-E participation (through the MOE) and the regulatory costs entailed by RES-E, divided by the amount of RES-E sold on the market. Positive values indicate that the costs incurred by RES-E exceed the savings, whereas negative values reflect the cost saving potential of RES-E. We also present the net effect for high (dashed line) and low (dotted line) demand periods in order to highlight the relevance of the demand in the accounting of RES-E costs.

After showing some fluctuations between 2003 and 2007, we observe that the mean unit net monetary cost started to grow steadily in 2007, but the market savings due to RES-E were still able to compensate for the regulatory costs until 2010. Afterwards, the unit net cost was always positive (between 27 and 38 EUR/MWh from 2011 to 2015). Figure 4 also shows that the last regulatory reform in 2014 did not reduce the unit net cost, although the phasing out of the FIT-FIP incentive scheme had the immediate effect of reducing the regulatory burden. The reduction of the MOE due to a lower renewable participation is behind the higher final unit net cost of RES-E.

[Insert Figure 4 here]

Concerning the effect of the demand patterns, Figure 4 shows that the unit net cost is higher when demand is low (dotted line) and lower when demand is high (dashed line). The discrepancy is due to the different technologies that RES replaces: more thermal production in high demand, with a higher cost. However, differences by demand diminish after 2013. This is partly due to the combination of lower electricity demand in the period with reduced hydropower participation and the last regulatory reform, which has also affected renewable participation in the pool.

4.2. Environmental Impact of RES-E

The deployment of RES-E displaces conventional sources of electricity generation that depend on combustion to generate electricity and emit GHG to the atmosphere as a by-product of the process. The most significant GHG of electricity generation is CO_2, but other gases that are potentially harmful for climate, such as SO_2 and NO_x, should also be taken into account. The purpose of this section is to assess the environmental impact of RES-E on the Spanish electricity market, by translating emission reductions into monetary values. Results are highly dependent on the methodology employed to monetize the emission savings, which highlights the role of uncertainty in the environmental benefits assessment.

Figure 5 shows the amount of energy by conventional sources that was displaced each year due to RES-E participation during the period 2002-2015. Note that when renewable participation peaks, the displaced share of the other technologies also increases. These figures are computed as the difference between the annual energy traded in equilibrium in the actual (with RES-E) and counterfactual (without RES-E) scenarios.

Combined cycle and hydropower are the most affected (since they usually are the marginal technologies setting the market price), followed by coal. The participation of fuel-gas in the Spanish pool is residual (in fact, it is zero after 2011) and is therefore barely affected by RES-E. Finally, nuclear power is also unaffected by RES-E given that it is a baseload technology.

[Insert Figure 5 here]

The replacement of conventional sources of energy has decreased the emissions of some pollutants. The avoided emissions are obtained by multiplying the emission potential for each pollutant (t/GWh) by the displaced amount (GWh) of each fossil technology: combined cycle, coal and fuel/fuel-gas. Table 4 shows the avoided emissions from 2002 to 2015 for CO_2, SO_2, NO_x and PM. Results are presented by energy source.

[Insert Table 4 here]

We observe that the largest avoided emissions are derived from the displacement of coal sources. Although the number of GWh displaced is higher for other technologies (e.g. combined cycle, see Figure 5), the environmental effect of RES-E on coal is the most relevant, given its high emission potential. Note also that the effect on avoided CO_2 emissions (measured in Mt) outweighs the other air pollutants (measured in kt).

Once we have computed the emission savings, we translate them into economic benefits. In order to do this, we need to price the emissions, for which we consider two different methodologies. Table 5 shows the savings in millions of euros of the avoided emissions using market prices. We use the EU ETS market price for CO_2 emissions and the US air market prices for SO_2 and NO_x (converting the prices in dollars to euros). Similarly, Table 6 shows the savings using the social cost methodology. We apply the SCC estimates used in US policy evaluation for CO_2 and derive the values for SO_2 and NO_x from the SCAR methodology by Shindell (2015). Given the data availability on emission prices, we present the results for the period 2008-2015 for CO_2 and only for the year 2010 for SO_2 and NO_x. Further research would be needed to compute social costs estimates for longer timeframes, but this is out of the scope of this paper.

As Table 5 illustrates, the volatility of the EU ETS price affects the emission savings accounting. This is particularly evident between 2011 and 2015, when the allowance price was around EUR 5-7, diminishing the economic effect of the greatest emission reduction due to RES-E.

[Insert Table 5 here]

Taking a look at the social cost approach in Table 6, we observe the variability of the results according to the selected discount rate (5%, 3% or 2.5%). High discount rates lead to lower savings than low discount rates, since the valuation today of environmental damages in the future is lower. The highest savings are obtained for the 95th percentile of the 3% scenario, which represents the low probability of very harmful climatic consequences. If we compare the economic quantification of the emission savings under the market and the social cost approach, we conclude that the environmental savings considering market prices after 2012 are lower than those with the highest rate considered in the SCC approach.

[Insert Table 6 here]

Comparing our results with Ortega, del Río and Montero (2013), which also monetize CO2 emissions reductions in Spain from 2002 to 2011, but using a different methodology, we observe that our market approach values for 2009, 2010 and 2011 are in their ranges when they use a CO2 price of 14 EUR/tCO2 (their values range from 322.2 to 239.5 million euros in 2009, from 376.5 to 259.3 in 2010 and from 269.0 to 390.1 in 2011).

4.3. The net social cost

Assuming that Spain is a price taker and would not be able to change emission allowance prices, we consider that emission prices would not vary in our counterfactual situation without RES-E and, therefore, this would not interact with the price reductions derived from the MOE. In this case, the environmental savings of RES-E computed in Section 4.2 could be added to the net monetary cost computed in Section 4.1 to determine the net social cost of RES-E.

Table 7 reports the unit net cost of RES considering the environmental benefits derived from the reduction of CO_2, as well as the net monetary cost. We observe that the valuation of the environmental benefits of CO_2 reduction is small compared to the net monetary cost. The results indicate that the promotion policy to RES implemented in Spain was justified in economic terms only until 2011. After that year, despite the environmental benefits, RES-E was not able to cover the huge regulatory costs. In fact, regulatory costs in Spain were over EUR 6 billion per year from 2009 onwards, and over EUR 9 billion euros in 2013, (see Figure 3), amounts impossible to compensate even with large environmental benefits.

[Insert Table 7 here]

A caveat is in order. Given that we were able to compute the savings due to SO_2 and NO_x only for one year (2010), these gases were not taken into account in the calculation of the unit net social cost. In any case, their contribution to the social cost in 2010 (the single year with available data) does not change the sign of the net social cost.

Finally, given that the net social cost is positive from 2011 onwards, we compute in Table 8 the CO2 price that would have led to zero social cost, that is, the CO2 valuation that would compensate the actual promotion costs of RES-E. We observe that carbon prices should have been around 100 EUR/tCO2 from 2011 to 2014 and close to 200 EUR/t CO2 in 2015, values that are much higher than the highest estimates for the social cost of carbon.

[Insert Table 8 here]

Compared with the literature, Marcantonini and Ellerman (2015) found an average implicit carbon price (i.e. net cost without carbon cost saving divided by CO2 emission reduction) of 57 EUR/tCO2 for wind power and 552EUR/tCO2 for solar energy in Germany (the huge difference between these two prices is attributed to the fact that the remuneration per MWh in Germany is much higher for solar than for wind, as it happens in Spain). Using the same methodology, Marcantonini and Valero (2017) found that average costs in Italy were around 165 EUR/tCO2 for wind power and around 1000 EUR/tCO2 for solar, higher than in Germany (again, due to the differences of the support levels). Our averages are in this range, taking into account that we consider all technologies as a whole, and that wind participation in Spain is much higher than solar.

5. Conclusions and Policy Implications

The promotion of RES-E implementation by the Spanish government reflects its commitment to signed international agreements in the fight against climate change. Initially this effort produced important savings in the system by reducing the electricity market price. However, the evolution of the regulatory costs of the RES-E has turned into a heavy burden for the Spanish electricity system. In fact, the savings due to RES-E could no longer compensate for the rapidly growing regulatory costs after 2010 (Ciarreta, Espinosa and Pizarro-Irizar, 2014).

In this paper, we computed the net effect of RES-E on the Spanish day-ahead market for the period 2002-2015 by comparing the net monetary cost (savings due to the merit order effect and the costs of the regulatory system) to the social environmental benefits of avoided emissions. Our conclusion is that, although important, the valuation of environmental benefits after 2011 did not justify the huge regulatory costs of RES-E promotion and as a consequence the promotion of RES-E had a positive net unit social cost (around 20 EUR/MWh) imposed on consumers.

The net unit social cost has been decreasing from 2011 to 2014, due to a regulatory reform (see Appendix A.2). The reform has brought about lower incentive levels and lower renewable participation. However, the overall effect of the new incentive scheme still remains unclear. On the one hand, subsidies have decreased with respect to the previous system based on tariffs and premiums, which had led to an increasing deficit in the Spanish electricity system until 2013 (in 2014 and 2015 there has been a surplus for the first time since 2000). Yet on the other hand, the lower incentives have reduced renewable participation and the merit order effect, increasing consumer prices. In any case, it is still soon to confirm if this fall in the RES-E share is due to the regulatory reform or is a consequence of other market conditions (market structure, demand, weather conditions…). This phenomenon would need further analysis in the coming years. Nevertheless, it is clear that in the last few years after the reform, the reduction in the MOE dominated over the regulatory cost reduction so that electricity reform may have backfired and increased the costs for consumers (the regulatory cost has decreased but prices at the pool are higher due to the MOE, so that the final price paid by consumers has increased).

These results raise important concerns about the economic implications of RES as a cost-effective mitigation resource. RES have displaced electricity generated by conventional sources, leading to a reduction of GHG emissions into the atmosphere. This phenomenon is remarkable when considering CO_2, the most significant and long-lasting GHG. To address this issue, we use two different methods to assess the economic value of RES-E environmental impact. First, we used the market price of the EU ETS system based on the "cap-and-trade" principle; and second, we took the social cost approach based on the SCC estimates for CO_2 and SCAR estimates for SO_2 and NO_x.

The assessment of the avoided emissions showed that even including the environmental benefits of RES-E, these sources are not able to cover for the regulatory costs after 2011. The reduced prices in the EU ETS system during the last years have led to very small emission savings valuation for RES-E. Finally, we also observed that the choice of the approach for evaluating the emissions is extremely important for policy analysis, since the unit net social cost was reduced with lower discount rates. However, what should be the optimal discount rate is still under debate.

This last evidence opens the door to other questions for future research. First, the low prices of the EU ETS system may encourage thermal electricity production, so it would be interesting to analyze to what extent these low prices could impact the RES-E deployment process and CO_2 emission reduction. Second, the savings due to avoided fuel imports would also add to the economic benefits of RES-E and, thus, should be considered. Finally, other non-environmental positive externalities should also be included in policy decision making, such as employment creation, health benefits or industrial development; as well as other costs entailed by the intermittency of some RES, such as back-up capacity cost, distribution and transmission costs, that could not be captured with the merit order effect.

Acknowledgements

We would like to thank the Ministry of Economy and Competitiveness and the European Regional Development Fund (ECO2015-64467-R, MINECO/FEDER), the Basque Government

(DEUI, IT-783-13) and the University of the Basque Country (PES14/63) for financial support. Finally, we are grateful to Gabriel Peto for his research assistance.

Notes

[1] Total primary energy supply considers: production + imports - exports - international marine bunkers - international aviation bunkers +/- stock changes.

[2] Annual average prices in the European Emission Trading system in 2013 were 4.45 EUR/tCO_2 (Sendeco2, 2016) and the mean SCC estimate in the studies analyzed by Tol (2012) is 49 EUR/tCO_2. The lowest mean SCC estimate (considering a 3% rate of time preference) is 5 EUR/tCO_2.

[3] Environmental externalities of renewable energy production can be divided into two categories that distinguish emissions of pollutants with global impacts (i.e. GHG) from those with local and/or regional impacts (i.e. pollutants other than GHG) (Owen, 2004).

[4] More precisely, they included 12 EU Member States plus Switzerland.

[5] For instance, Nordhaus (2007) calculated an optimal price of carbon for 2015 of \$35/tCO_2, rising over time to \$85 in 2050 and to \$206 in 2100. Wahba and Hope (2006) estimated a SCC mean value between \$14/tCO_2 and \$19/tCO_2, depending on the selected scenario.

[6] See Johnston (2016) for a detailed description of SCC estimates.

[7] Howard and Sterner (2017) propose a new damage function based on different high-temperature damage estimates and conclude that this change would increase the resulting SCC of the Interagency Working Group by between one-and-a-half to twofold.

[8] Differences in methodology may include different assumptions about emission scenario, climate sensitivity, impact estimates, adaptation, valuation, vulnerability, equity weighting, and risk aversion (Tol, 2012).

[9] We do not consider intra-day markets and technical restrictions in our analysis and we work with day-ahead market prices rather than with final prices. Ciarreta, Espinosa and Pizarro-Irizar (2014) use a similar approach, since the day-ahead market stands for more than 80% of the final price.

[10] For a detailed explanation of this algorithm see Ciarreta, Espinosa and Pizarro-Irizar (2014).

[11] *Operador del Mercado Ibérico de Electricidad.*

[12] *Comisión Nacional de los Mercados y la Competencia.*

[13] We use the classification of the Spanish Ministry of Economy: 8 high-demand-hours and 5 low-demand-hours in daily electricity consumption, different for summer and winter (BOE, 2001).

[14] CO_2 policies are usually directed at a global level, whereas air pollutants are generally targeted at a local scale (city, country level). However, there is some support for policies designed to address them jointly (Bollen et al., 2009 and Xu and Masui, 2009).

[15] The Clean Air Act directs the U.S. Environmental Protection Agency to identify and set air quality standards for the following air pollutants: Ozone (O3), Carbon monoxide (CO), Nitrogen oxides (NOx), Sulfur dioxide (SO_2), Particulate matter with aerodynamic diameter less than or equal to 10 micrometers (PM10), Particulate matter with aerodynamic diameter less than or equal to 2.5 micrometers (PM2.5), and Lead (Pb). Given the public data availability we focus on SO2 and NOx.

Appendix: Renewable energy promotion on the Spanish electricity market

Spain is committed to the EU's climate policy (Section A.1), but it also has strong national policies (Section A.2). The analysis of these policies is important to understand the development of RES-E in the past. Additionally, the Spanish electricity market rules are another key factor to assess the economic implications of RES-E (Section A.3).

A.1. Policy Framework in the European Union

The EU has been implementing a common policy framework for facing the climate change challenge for several years. Specifically, the Energy and Climate Change Package 2013–2020 contains four directives for common EU legislation: on the amendment to the EU ETS, on the promotion of RES, on effort sharing, and on carbon capture and storage (Jäger-Waldau et al., 2011).

The EU ETS is a cap-and-trade emission scheme for CO_2. The system imposes an aggregated emission cap for all the CO_2 emitters and a trading system is implemented among them, thus resulting in a CO_2 price (Delarue and van den Bergh, 2016). The EU ETS is the largest international system for trading GHG emission allowances, operating in 31 countries and covering different sectors, such as the electricity power sector, other heavy industries (cement, steel, aluminum, pulp and paper) and aviation (flights within Europe), and almost half of the EU's greenhouse emissions (EU, 2013).

The EU ETS was implemented in 2005 and has been deployed in three different phases (EU, 2016). Phase I was implemented from 2005 to 2007, only CO_2 emissions from power plants and energy-intensive industries were considered and almost all the allowances were given for free through the National Allocation plan. Phase II, between 2008 and 2012, implied a slight reduction of the cap and auction were carried out in several countries. Finally, Phase III comprises from 2013 to 2020 and implies the implementation of a single EU cap, auction is recognized as the method for allocating allowances and its rules have been harmonized.

Concerning the promotion of RE, Directive 2009/28/EC set a common framework for the EU in 2009. The Directive established mandatory national targets for the overall share of energy from renewable sources in gross final consumption. In detail, such mandatory national overall targets were consistent with a binding target of at least a 20 % share of energy from renewable sources in the gross final energy consumption in 2020, including individual targets by country. For achieving this goal, each Member State designed and implemented support schemes at a national level.

From a national perspective, a broad range of support schemes has been deployed in the promotion of RES-E. There are two broad categories of market based instruments (IEA 2008): investment support (capital grants, tax exemptions or reductions on the purchase of goods) and operating support (price subsidies, green certificates, tender schemes and tax exemptions or reductions on the production of electricity). Among them, FIT has been considered the most effective scheme for encouraging the exponential growth of RES-E in the EU (Couture and Gagnon, 2010 and Jenner, Groba, and Indvik, 2013).

The central principle of the FIT is the establishment of granted prices for RES-E producers during fixed periods of time (Couture and Gagnon, 2010). This policy design is divided into market-independent and market-dependent FIT policies regarding the remuneration model. The former is known as fixed-price policy and sets a fixed or minimum price for RES electricity delivered to the grid. The latter, named premium-price policy or FIP, adds a premium to the market price. In summary, fixed-price policy implies the total price per unit of electricity paid while premiums are supplementary to the market price. The special feature of the FIT guarantees in advanced the payment level, thus offering security for the investments in RES-E by granting reliable revenue streams. On the other hand, FIP creates more efficient markets by allowing the remuneration adjust to the market demand, creating an incentive to supply electricity when demand increase.

A.2. RES-E Generation and Policy Evolution in Spain

Since the 1980s, the Spanish electricity legislative framework has been modified and adapted to promote RES-E implementation. In 1997, the Electricity Sector Act (Act 54/97) (BOE, 1997) established the Special Regime (SR) to distinguish renewable from conventional (Ordinary Regime, OR) fuel sources of electricity. The SR included renewable technologies (onshore wind, solar photovoltaic, solar thermal, small-scale hydropower, biomass, wastes and waste treatment) and cogeneration with capacity below 50 MW.

In 2004, the Spanish Renewable Energy Act (RD 436/2004) (BOE, 2004) was set up to fit into the existing general framework supporting RES-E. Generators could decide to sell their electricity to a distributor and receive a fix tariff (FIT) or sell it on the free market and receive a premium on top of the market price (FIP), what we call the FIT-FIP system. This decree provided incentives for new RES installed capacity and led to the actual took off of RE in Spain.

The steeped growing trend of the RES-E generation continued for almost a decade, nevertheless accompanied by continuous adjustments of the support schemes, in an attempt to reduce the costs of the incentive system. In 2007, new tariffs and premiums for RES-E generators were established in the New Spanish Renewable Energy Act, as well as a cap and a floor for renewable remuneration (RD 661/2007) (BOE, 2007) and this led to the greatest renewable energy expansion in Spain.

Between 2010 and 2014 a series of legal actions were issued regarding financial adjustments, in an attempt to reduce the tariff deficit that arose due to the imbalance between the revenues and the costs of the Spanish electricity system. In 2010, the RES-E production level reached 94,101 GWh in 2010, nearly 50% of the Spanish electricity market. That same year the government enacted RD 1614/2010 (BOE, 2010) for adjusting downward the FIT of the wind generation technology. In 2012, the financial support for RES-E facilities (RD-L1/2012) (BOE, 2012) was abolished. One year later, the premiums for RES power generation were suppressed (RD-L2/2013) (BOE, 2013a) and the FIT were revoked and replaced by a flat fee investment incentive (RD-L9/2013) (BOE, 2013b). As a result of the measures, the year 2013 represented a turning point of the RES power generation after its production peaked at 110,455 GWh.

Finally, the RD 413/2014 (BOE, 2014) published in mid-2014 established a new remuneration scheme in order to provide a rate of return in addition to the electricity market price. This measure was followed by a smooth decline of RES-E between 2014 and 2015. However, in spite of the downturn during the last two years of the period, the RES-E production share on the Spanish electricity market in 2015 was still above 50%.

[Insert Figure A.1 here]

Figure A.1 shows the relationship between RES-E evolution and the policies deployed along the period. In that sense, the highest RES-E growth came after the Renewable Energy Act and the New Renewable Energy Act in 2004 and 2007, respectively. However, the more restrictive policies implemented after 2010 led to smaller RES-E growth rates and even a reduction of the RES-E share after the phasing out of the FIT-FIP system in 2013.

Concerning the financial burden of the Spanish electricity system shown in Figure A.2, we observe that the trend of previous annual deficits ended in 2014, where there was a surplus for the first time since 2000. This surplus is the result of the regulatory reform of the electricity sector, which stated a new incentive scheme for RES-E in 2014, but with retroactive effects since 2013. That is, SR generators continued receiving the corresponding FIT during the period between the phasing out of the tariffs and the establishment of the new procedure to set the incentives. This forced some RES-E generators (mainly wind and cogeneration) to return the received incentives during 2013 and 2014 if their value under the former scheme was higher than the support they should get under the new system. The evolution of the deficit in the next years will tell whether this surplus persists over time or it is just a temporary effect derived from the adjustment in the liquidations. In any case, despite the positive results in 2014 and 2015, the electricity system's accumulated debt still amounted to EUR 25 billion at the end of 2015 (Ciarreta, Espinosa and Zurimendi, 2016).

[Insert Figure A.2 here]

A.3. The Spanish Day-ahead Market

The wholesale electricity price in the Iberian Peninsula is determined by a set of markets. The electricity system comprises the day-ahead (or daily market), intra-day markets and the ancillary services market. According to the Electricity Market Operator (in short OMIE), the daily market accounts for more than 80% of the final day-ahead market price, while the intraday market, technical restrictions, capacity payments and other processes of the system operator explains the other 20% (OMIE, 2016). For that reason we will focus on the day-ahead market.

The day-ahead market is the mechanism for handling bids on a daily basis (OMIE, 2016). It is performed once a day at noon to set the amount and price of the electricity exchanged for each of the twenty-four hours of the following day. The day-ahead market manages the sale and purchase bids that are presented by market participants. The bids can be presented in two ways: simple and complex. The simple ones only include price and amount of energy; the complex ones incorporate other technical or economic features. The market participants are the sellers represented by electricity generation companies and the buyers include consumers and retailers.

The day-ahead market works as a uniform price double auction which determines the market clearing price and energy traded by the intersection point between the supply and demand curves. The curves are constituted by sorting the bids by its price: the supply curve is built in an ascending order, while the demand curve is built in a descending order. The framework implies that electricity generators maximize their benefits by bidding their opportunity cost, thus maximizing the probability of being selected for supplying electricity (Gallego-Castillo and Victoria, 2015).

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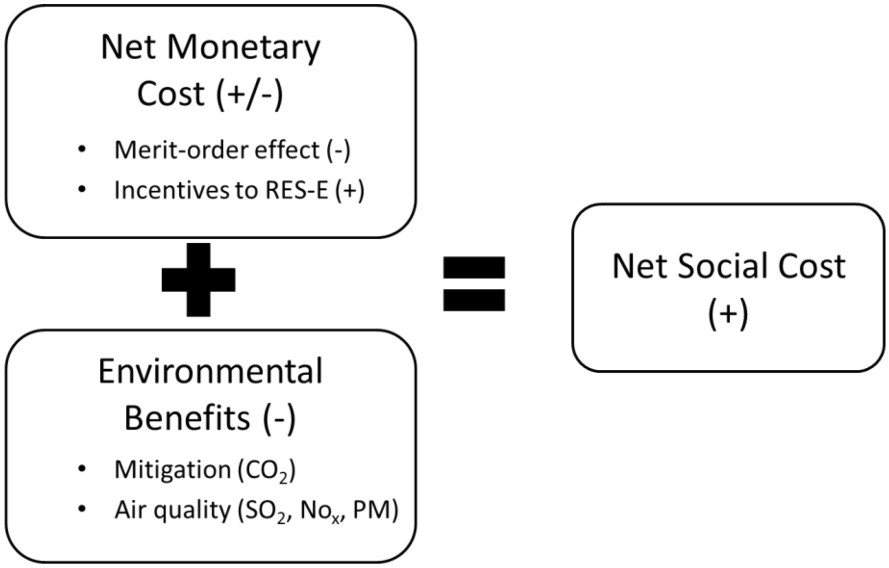
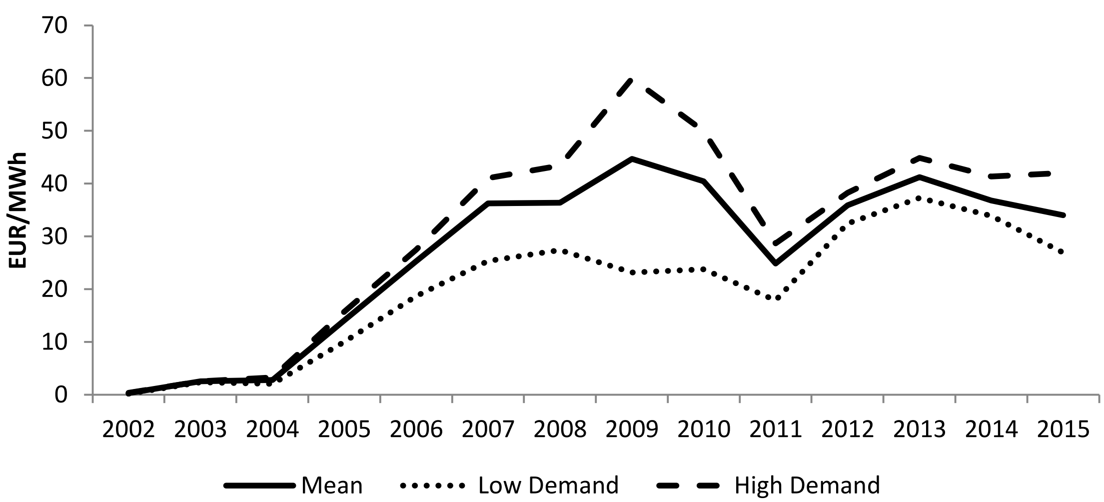
Figures

Figure 1. The net social cost of RES-E promotion



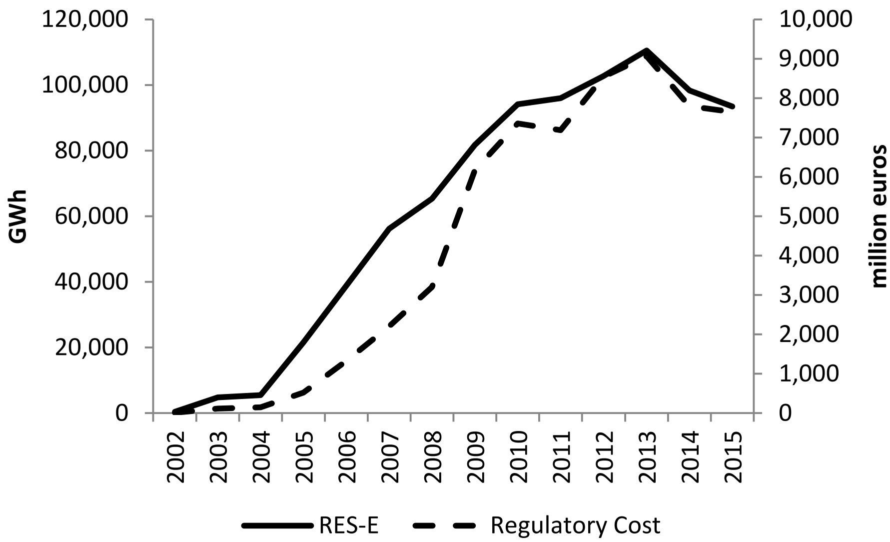
Note: The negative sign (-) stands for benefits and the positive sign (+) stands for costs.

Figure 2. Price reduction due to RES-E by demand (EUR/MWh)



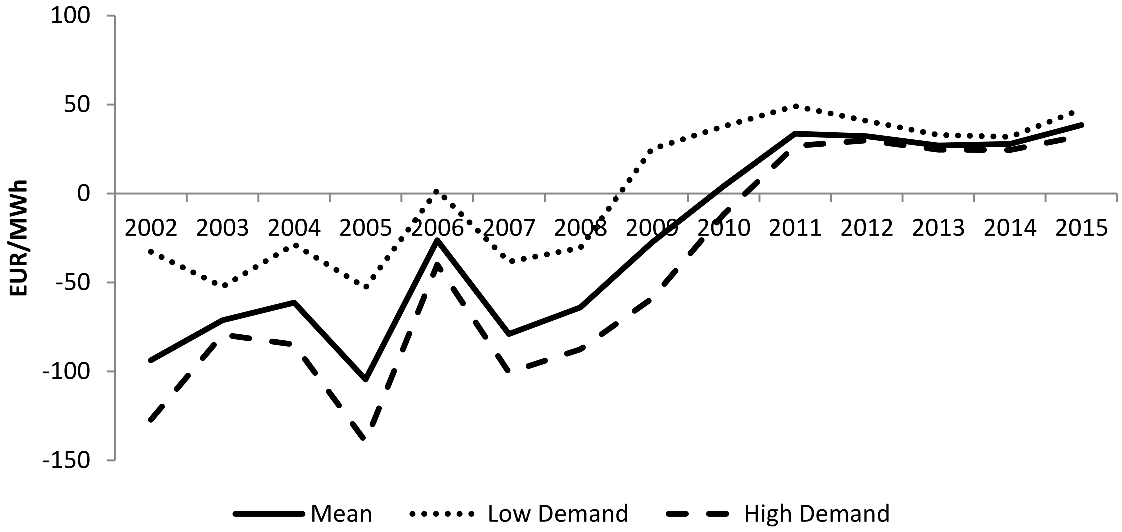
Source: Own calculations based on data from OMIE (2016).

Figure 3. Annual RES-E participation in the day-ahead market (GWh) and annual regulatory cost (million euros)



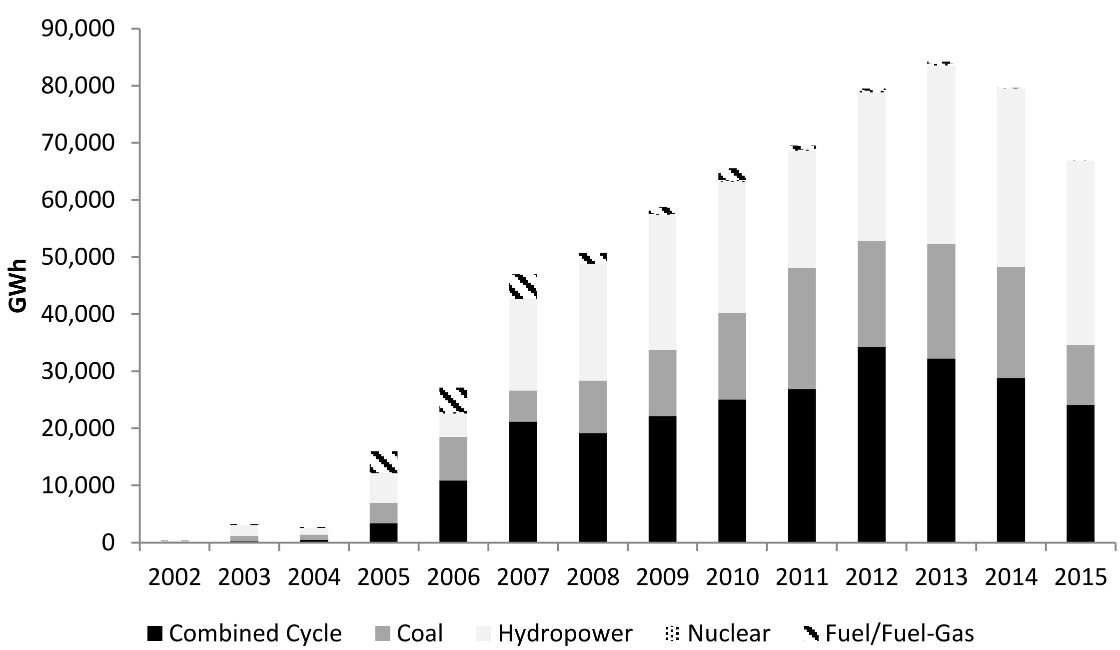
Source: Own calculations based on data from OMIE (2016) (RES-E participation) and CNMC (2015) (regulatory cost).

Figure 4. Unit net monetary cost of RES-E promotion by demand (EUR/MWh)



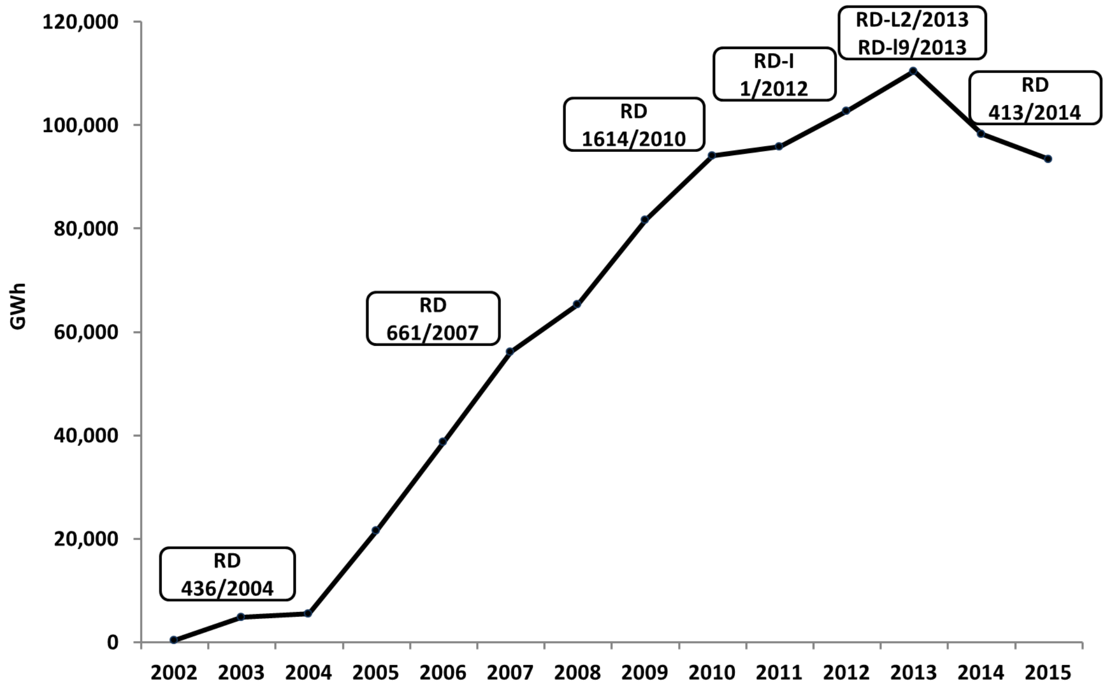
Source: Own calculations based on data from OMIE (2016) and CNMC (2015).

Figure 5. Energy displaced due to RES-E by technology (GWh)



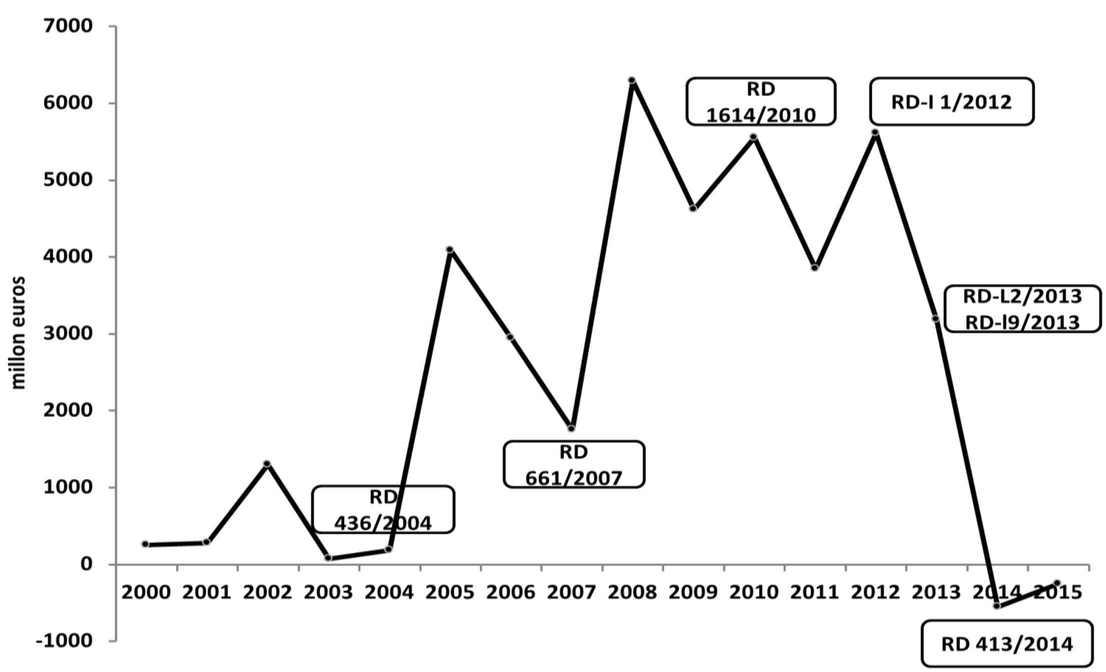
Source: Own calculations based on data from OMIE (2016).

Figure A.1 RES-E generation evolution and policy milestones, 2002-2015 (GWh)



Source: Own elaboration based on OMIE (2016) and IEA (2015).

Figure A.2 Tariff deficit evolution and policy milestones, 2000-2015 (million euros)



Source: Own elaboration based on Ciarreta, Espinosa and Zurimendi (2016).

Tables

Table 1. Social Cost of Carbon. Estimates for 2020

Country	Mean	Range	Reference
EU	49 EUR/tCO_2	10-439 EUR/tCO_2	Tol, 2012
UK	90 £/tCO_2	55-160 £/tCO_2	Watkiss and Downing, 2008
US	42 \$/tCO_2	12-123 \$/tCO_2	IWG, 2016

Note about mean values: Tol (2012) aggregates all available estimates into a single distribution (including different discount rates), Watkiss and Downing (2008) consider a 3.5% discount rate and IWG (2016) a 3% discount rate.

Source: Own elaboration based on Watkiss and Downing, (2008), Tol (2012) and IWG (2016).

Table 2. Annual SCC estimates (2007-constant \$/tCO_2)

	Discount Rate			
	5%	3%	2.5%	3%
	Average	Average	Average	95th percentile
2008	10	29	48	79
2009	10	30	49	82
2010	10	31	50	86
2011	11	32	51	90
2012	11	33	53	93
2013	11	34	54	97
2014	11	35	55	101
2015	11	36	56	105

Source: IWG (2016) and own elaboration for 2008 and 2009 (based on the growth rate from 2010 to 2015 estimates).

Table 3. Annual SCAR estimates in $/t$SO_2$ and $/t$NO_x$ (2007-constant dollars)

	Discount Rate			
	SO_2		NO_x	
	5% Average	3% Average	5% Average	3% Average
2010	45	47	26	26

Source: Own elaboration based on data from Shindell (2015) and IWG (2016).

Table 4. Avoided emissions by pollutant and technology: CO_2 (Mt), SO_2 (kt), NO_x (kt) and PM (kt)

year	Combined Cycle				Coal				Fuel/Fuel-Gas				TOTAL			
	CO_2 (Mt)	SO_2 (kt)	NO_x (kt)	PM (kt)	**CO_2 (Mt)**	SO_2 (kt)	NO_x (kt)	PM (kt)	**CO_2 (Mt)**	SO_2 (kt)	NO_x (kt)	PM (kt)	**CO_2 (Mt)**	SO_2 (kt)	NO_x (kt)	PM (kt)
2002	**0.01**	0	0	0	**0.098**	1.70	0.30	0.04	**~0**	~0	~0	0	**0.11**	1.71	305	0.04
2003	**0.07**	0	0	0	**0.96**	14.18	3.10	0.36	**0.08**	0.27	0.11	0.01	**1.11**	14.45	3.22	0.37
2004	**0.18**	0	0	0	**0.85**	13.28	2.88	0.32	**0.12**	0.36	0.18	0.02	**1.15**	13.64	3.06	0.34
2005	**1.20**	0	0	0	**3.36**	52.42	11.08	1.26	**1.37**	4.13	2.16	0.18	**5.93**	56.55	13.23	1.44
2006	**3.88**	0	0	0	**7.13**	111.78	23.80	2.48	**1.38**	3.93	2.14	0.18	**12.39**	115.71	25.95	2.65
2007	**7.55**	0	0	0	**5.12**	76.63	16.58	1.63	**1.31**	3.21	1.86	0.17	**13.99**	79.84	18.43	1.80
2008	**6.60**	0	0	0	**8.75**	33.23	21.46	2.31	**0.29**	1.87	1.10	0.11	**15.64**	35.10	22.56	2.42
2009	**7.93**	0	0	0	**10.96**	38.48	24.59	2.60	**0.23**	0.47	0.30	0	**19.12**	38.95	24.90	2.60
2010	**8.76**	0	0	0	**14.44**	47.04	28.79	3.41	**1.53**	2.57	1.84	0	**24.74**	49.61	30.62	3.41
2011	**9.69**	0	0	0	**20.01**	60.59	44.59	4.78	**0**	1.03	0.96	0	**29.70**	61.62	45.54	4.78
2012	**12.67**	0	0	0	**17.39**	57.08	40.79	4.18	**0**	0.59	0.47	0	**30.06**	57.67	41.26	4.18
2013	**11.92**	0	0	0	**18.78**	61.63	44.04	4.51	**0**	0.61	0.49	0	**30.70**	62.24	44.53	4.51
2014	**10.65**	0	0	0	**18.26**	59.91	42.81	4.38	**0**	0.13	0.10	0	**28.91**	60.04	42.91	4.38
2015	**8.91**	0	0	0	**9.88**	32.42	23.16	2.37	**0**	0	0	0	**18.79**	32.42	23.16	2.37
TOTAL	**90.01**	0	0	0	**136.00**	660.38	327.97	34.63	**6.31**	19.17	11.71	0.66	**232.33**	679.55	339.68	35.30

Source: Own calculations based on data from OMIE (2016) and CNMC (2015).

Table 5. Valuation of Avoided Emission (million euros) under a market approach, by technology

year	Combined Cycle			Coal			Fuel/Fuel-Gas		
	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
2008	145	0	0	193	6	12	6	0.4	0.6
2009	104	0	0	143	2	5	3	0.0	0.1
2010	125	0	0	207	1	1	22	0.0	0.1
2011	125	0	0	258	0	1	0	0.0	0.0
2012	93	0		128	0		0	0.0	
2013	53	0		84	0		0	0.0	
2014	63	0		109	0		0	0.0	
2015	68	0		76	0		0	0.0	
TOTAL	777	0	0	1,196	9	18.6	31	0	0.7

Source: Own calculations based on data from OMIE (2016) and Sendeco2 (2016).

Table 6. Avoided emission benefits: market approach vs. social cost approach (million euros)

year	CO_2					SO_2			NO_x		
	Market approach	Social cost approach				Market approach	Social cost approach		Market approach	Social cost approach	
		5%	3%	2.5%	3% 95th percentile		5%	3%		5%	3%
2008	344	104	316	518	858	6.6			12.4		
2009	250	138	423	688	1,162	2.3			5.4		
2010	354	194	602	970	1,669	0.6	1.75	1.83	1.03	0.62	0.62
2011	383	249	725	1,155	2,038	0.1			0.5		
2012	220	278	835	1,340	2,352						
2013	137	279	863	1,371	2,463						
2014	172	267	850	1,336	2,454						
2015	144	210	687	1,069	2,005						
TOTAL	2,005	1,720	5,302	8,448	15,001						

Source: Own calculations based on data from OMIE (2016), Shindell (2015) and IWG (2016).

Table 7. Monetary and Environmental Impact of RES promotion

year	Net Monetary Cost (EUR/ MWh)	Net Unit Social Cost of RES (EUR/MWh)					
		Market Approach to environmental damage	Social Cost Approach to environmental damage			
			5%	3%	2.5%	3 % 95th percentile
2008	**-64.1**	**-69.4**	**-65.7**	**-69.0**	**-72.1**	**-77.3**
2009	**-27.6**	**-30.7**	**-29.3**	**-32.8**	**-36.1**	**-41.9**
2010	4.1	0.4	2.1	**-2.2**	**-6.2**	**-13.6**
2011	33.6	29.7	31.0	26.1	21.6	12.4
2012	32.1	30.0	29.4	24.0	19.1	9.2
2013	26.9	25.6	24.3	19.0	14.4	4.6
2014	27.8	26.0	25.1	19.1	14.2	2.8
2015	38.5	36.9	36.2	31.1	27.0	17.0

Note: Negative values indicate that RES promotion involves a net social benefit. Net Unit Social Cost of RES includes the Net Monetary Cost and the environmental benefits.

Source: Own calculations based on data from OMIE (2016), CNMC (2015) and Sendeco2 (2016).

Table 8. CO_2 price for a zero net social cost (EUR/tCO_2)

	2011	2012	2013	2014	2015
CO_2 price	108.7	109.8	96.6	94.5	191.3

Source: Own calculations.