Energy for Sustainable Development 29 (2015) 47–56

Contents lists available at ScienceDirect

Energy for Sustainable Development

Economical–environmental impact of subsidised renewable energy sources for electricity (RES-E) in the Spanish system

D. Azofra [a,1], E. Jiménez [b,2], E. Martínez [a,1], J. Blanco [a,*], J.C. Saenz-Díez [b,2]

[a] Department of Mechanical Engineering, University of la Rioja, Edificio Departamental — C/Luis de Ulloa, 20, 26004 Logroño, La Rioja, Spain
[b] Department of Electrical Engineering, University of la Rioja, Edificio Departamental — C/Luis de Ulloa, 20, 26004 Logroño, La Rioja, Spain

ARTICLE INFO

Article history:
Received 24 June 2014
Revised 26 August 2015
Accepted 10 September 2015
Available online 18 October 2015

Keywords:
RES-E
Cost–benefit analysis
Greenhouse and hazardous gas emissions
Merit order effect
Fossil fuel supply problems

ABSTRACT

In 2012, Spain obtained 68.5 TWh of its electricity (25% of the total) from renewable energy sources excluding large hydroelectric power (RES-E). Subsidies, through feed-in-tariffs, for various forms of RES-E ranged from 40.2 €/MWh to 321.1 €/MWh and totaled 6.1 billion E, an amount that has motivated substantial criticism. This paper examines the effects of RES-E on the market price of electricity considering the merit order effect in Spain's power auction system. The M5P algorithm developed by Quinlan (1992) is used to calculate changes in the settling price in daily power auctions. Also, the value of emissions of CO_2, NO_x, and SO_x avoided through RES-E is calculated. They are valued at $10/t, $478/t, and $1460/t, respectively. Results of the analysis show that, in 2012, RES-E caused an estimated 3.1 B€ savings in electricity expenditures due to market effects and a 0.7 B€ saving in emission costs. When subtracted from the total subsidy a net cost of RES-E of 2.3 B€ is derived. Wind, biomass, and small hydroelectric had negative net costs (i.e., net benefits) while photovoltaic and solar-thermal power had net costs. Alternative scenarios in which the production of gas-fired and coal-fired electric power are individually curtailed by 30% in comparison to the baseline scenario, while RES-E is held at the 2012 level, yielded a net cost decrease of about 300 M€ for gas curtailment and a net cost increase of about 300 M€ for coal curtailment.

Introduction

Despite the progress made in social awareness of global warming and pollution, the world is still far from reaching a change of trend to reverse the situation (the level of carbon dioxide in the air in May 2013 reached as high as 400.03 ppm — NOAA, 2014). However, Spain has finally realised that dependence on fossil fuels can no longer be prolonged and renewable energies are becoming stronger over time within the global generation mix. RES-E excluding large hydroelectric (referred as RES-E from now on) in Spain increased from 15.4 TWh in 2002 to 68.5 TWh ten years later (see Table 1), accounting for almost 25.0% of the total generation in 2012 (REE, 2003, 2013a,b). Nevertheless, not all the renewable alternatives offer the same degree of sustainability and technological maturity.

Spanish electricity system

As commanded from European Community, a free market for the Spanish electric system, i.e., a wholesale electricity auction, was settled. Three different institutions were dedicated to make it possible. OMI-POLO ESPAÑOL, S.A. (OMIE) controls the market from an economical side, settling supply and demand. Red Eléctrica de España, S.A. (REE) was established to control the new market from a technical side, ensuring that electricity reaches final consumers. Finally, CNE (Comisión Nacional de la Energía), as a third party, is dedicated to ensure effective competiveness and market transparency.

The core of the wholesale market (known as *pool*) is the daily auction where most wholesale electricity is bought and sold. All generation facilities not affected by bilateral contracts (of power supply) are required to submit offers for the daily market. In the Spanish electricity system, RES-E has the right to a subsidy known as feed-in-tariff because it belongs to the Special Regime[3] of power generation and therefore

* Corresponding author. Tel.: +34 941 299 524.
E-mail addresses: diego.azofra@alum.unirioja.es (D. Azofra), emilio.jimenez@unirioja.es (E. Jiménez), e.camara@eolicas.net (E. Martínez), julio.blanco@unirioja.es (J. Blanco), juan-carlos.saenz-diez@unirioja.es (J.C. Saenz-Díez).
[1] Tel.: +34 941 299 524.
[2] Tel.: +34 941 299 502.

[3] Term that includes the facilities that use sources or resources of renewable energies, wastes, and co-generation. It was stated by Royal Decree 2818/1998, that stated a specific regulation of energy production by adjusting to the regulations of Law 54/97. This support scheme offsets the gap between the costs of generation with these clean technologies and traditional power generation plants as well as it ensures that RES-E will be matched in the wholesale electricity auction.

http://dx.doi.org/10.1016/j.esd.2015.09.002
0973-0826/

Table 1
Electricity generation by source in 2002, 2008 and 2012 (REE, 2003, 2013a,b).

Electricity generation [TWh]	2002	2008	2012
Special regimen	34.1	68.0	102.2
Wind power	8.7	31.8	48.1
Photovoltaic power	0.0	2.4	7.8
Biomass power	1.7	2.7	4.7
Solar–thermal power	0.0	0.0	3.4
Small hydroelectric power	3.8	4.6	4.6
Non-renewable thermal power	20.0	26.6	33.4
Ordinary regimen	177.9	212.0	166.3
Nuclear	63.0	59.0	61.5
Coal	78.8	46.3	54.7
Oil	21.8	2.4	0.0
NGCC		91.3	38.6
Large hydroelectric power	22.6	21.4	19.5
Generation consumption	−8.3	−8.3	−7.9
Total	212.0	280.0	268.5

present their electricity sale bids to zero price in order to be matched in the auction. From this point on, the rest of the facilities (covered by Ordinary Regime Scheme) enter into the auction. Nuclear, NGCC, coal-fired and large hydroelectric facilities bid their production, increasing prices step by step, until demand is served. Since the auction is a marginal auction type, the matched price of the latest MWh needed to cover demand sets the market-clearing price for the wholesale electricity *pool*.

RES-E scheme — continuous regulatory changes

The context of promotion of the special regime has varied significantly in recent times due to two main reasons:

- In 2007 the Spanish government deeply decided to promote RES-E by increasing the subsidies and not establishing a power capacity limit for its deployment along the time. That supposed a very high cost for the electric system in a very short time.
- Once the government realised that the subsidies were out of control, decided to start applying measures to reduce cost. So, from 2008 on several new regulations were (some of them retroactively) promulgated and the RES-E were pointed out as expensive and the reason of the Spanish electric system deficit.

In following paragraphs, the regulatory changes summarized above are presented in detail:

Royal Decree 661/2007 appears after the approval of the PER (Renewable Energies Plan) 2005–2010 whose objective was to cover 12.1% of the total energy demand of Spain and the 30.3% of the total power consumption with renewable sources for the year 2010. The subsidies of the special regime generation are significantly increased in order to promote RES-E in Spain. No limit for installed annual power t is determined allowing a RES-E boom in the Spanish electric system.

Royal Decree 1578/2008 appears due to the need of controlling the excessive growth underwent by photovoltaic energy after the Royal Decree 661/2007. It fits the bonuses to the price fall experienced by solar panels and determines an exhaustive control of the maximum annual power to be installed.

Royal Decree 1565/2010 establishes urgent measures to correct the tariff deficit of the energy sector, modifying certain aspects of the Law 54/1997 of the Energy Sector, among which stand out the limit of equivalent hours with right to subsidy is introduced for photovoltaic facilities based on its technology and climate zone.

Royal Decree 1/2012 suppressed the incentivizing economic regimes for certain special regime facilities, imposing therefore a moratorium on new facilities.

Royal Decree-Law 2/2013 obliged renewable energy facilities to follow a regulated tariff (so that the possibility of market price plus a bonus was no longer available).

Royal Decree-Law 9/2013 suppressed the bonuses to renewable energies as such are and in exchange a “reasonable” profitability is guaranteed for a period of 25 years (from 2001 to 2026), equivalent to a 7.5%.

All these last measures are focused on reducing the cost of promoting the development of RES-E in the Spanish power system pointed out as expensive and the main reason for the deficit of the electric system.

Effect of RES-E

However, RES-E also has indirect economic impacts on the system. Since bilateral contracts are out of the pool and production from RES-E is always matched in it, there is less electricity demand to be covered by the Ordinary Regime, hence depressing the price they have to offer to be matched in the *pool*, and therefore the final matched price of the auction. It may happen that the savings derived from a lower settling price were greater than the subsidies received by the technologies covered under the Special Regime. This is known as the Merit Order Effect.

Furthermore, renewable energies lead to health, environment and climate benefits as they displace conventional thermal power plants from the generation mix, thus reducing the emissions of pollutant gases such as:

- hazardous air pollutants known or suspected to cause cancer or other serious health effects or adverse environmental effects (this includes SO_2, NO_x, etc.);
- greenhouse gases which absorb part of the infrared radiation emitted by the Earth's surface when heated by the sun, thus increasing the atmospheric temperature.

Literature review

Direct (feed-in tariff) and indirect (merit order effect) economic impacts

The economic influence of the RES-E, accounting for both the direct (feed-in tariff) and indirect (merit order effect) influences, has brought the attention of the scientific community as long as the deployment of these technologies on the generation mix has become relevant. Sensfuß et al. (2008) analysed the impact of subsidised renewable electricity generation on the electricity market in Germany. The central aspect analysed is the impact of renewable electricity generation on spot market prices. The results generated by an agent-based simulation platform indicate that the merit order of renewable energies (specifically wind power) in the *pool* made the price of electricity drop by €7.83/MWh. Also for Germany, Weigt (2009) stated that wind power is profitable to the system in economic terms.

Forrest and MacGill (2013) determine that the merit order effect of wind power in the Australian system caused a drop in energy prices of $8.05/MWh for South Australia and $2.73/MWh for Victoria. Also for the Australian case, McConnell et al (2013) analysed the hypothetical introduction of 5 GW of photovoltaic energy into the generation mix, estimating a saving of $628 million and $1200 million for 2009 and 2010 respectively. Those cures represent 8.6% and 12% of the value traded for those years respectively.

For the specific case of the Spanish electricity *pool*, Sáenz de Miera et al. (2008) indicate that wind power generation caused a decrease in the wholesale electricity price of €7.08/MWh in 2005, €4.75/MWh in

2006 and €12.44/MWh in the first quarter of 2007. Along similar lines, Gil et al. (2012) show that wind power generation caused a reduction of €9.72/MWh in *pool* spot prices from 2007 to 2012. The Spanish special regime as a whole has also been studied. Gelabert et al. (2012) determine that an increase of 1 GWh of electricity by means of renewable sources and co-generation causes a price reduction of nearly €2/MWh. Burgos-Payán et al. (2013) assert that each TWh of generation from renewable energies reduces the price by €0.11/MWh.

Azofra et al. (2014a) quantify for the first time the merit order effect produced individually for solar-thermal power, small hydroelectric and biomass in the Spanish electricity system in 2012. They conclude that these three technologies lowered the final price of electricity in the spot market by €1.05, €1.45 and €1.48/MWh respectively. This paper represents the basis of this new research but accounting this time for hazardous and GHG emission reduction as well as extending the analysis to two alternative scenarios that simulate possible eventualities in coal and natural gas supplies. Regarding the latter, the authors have not found in the scientific literature up to now a detailed analysis on how the influence of RES-E on the electric system is affected by the reduction in the generation of any of the mains fossil-fuelled thermal technologies. Taking into account the current conflict-ridden international situation and the ongoing process of restructuring of the Spanish power system, it is now considered plausible and necessary to analyse the effects of eliminating energy supplies from external gas sources, as well as variations in the regulatory framework for domestic coal that may bring the energy sector to a standstill. In this sense, to simulate hypothetical supply problems in foreign gas, a scenario with a 30% reduction in generation from NGCC is generated. On the contrary, the second scenario considers a coal-fired generation fall of 30%.

Reduction of pollutant gases: economic assessment

Emissions are quantified by means of Life Cycle Assessment (LCA) that evaluates the overall environmental impacts of each generation technology. Over the past years a large body of literature has built up on this topic. Pehnt (2006), investigates a dynamic approach towards the LCA of renewable energy technologies and proves that for all renewable energy chains, the inputs of finite energy resources and emissions of greenhouse gases are extremely low compared with the conventional system. Turconi et al. (2013) present a critical review of 167 case studies involving the life cycle assessment (LCA) of electricity generation based on hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic (PV) and wind, carried out to determine ranges of emission for GHG, NO_x and SO_2 related to individual technologies. Akhgari and Kalaman (2013) develop an economic and environmental assessment of utilising renewable energies compared to natural gas with a view to choosing the economically & environmentally best alternative for power generation. Equivalent uniform annual value and scaling-weighting check lists with expert comments obtained via an analytical hierarchy process are applied for economical and environmental assessment, respectively. The results of normalised economic and environmental assessments are subsequently coalesced to gain a combined economic–environmental perspective.

Regarding the case of Spain, Burgos-Payán et al. (2013) present an overview of the production of electricity from renewable sources (PE-RES) and draw up an initial analysis of the economic & environmental impact generated by renewable energies in 2005–2011.

The present paper is based on Akhgari and Kalaman (2013) for the emissions caused by Wind power, photovoltaics, biomass and small hydroelectric. Emissions caused by solar–thermal power facilities have been derived from Pehnt (2006).

Artificial intelligence techniques applied for electric system analysis

Machine learning has been applied with good results for the prediction (ex-ante) of the price of electricity in the Spanish electricity *pool*. Cruz et al. (2011) empirically compare the predictive accuracy of a set of methods for day-ahead spot price forecasting in the Spanish electricity market. The methods come from time series analysis and artificial intelligence disciplines, and include univariate, multivariate, linear and nonlinear. Within the univariate methods, double seasonal ARIMA and exponential smoothing for double seasonality are compared and used as benchmarks. Pino et al. (2008) calculate next-day hourly forecasts for energy prices in Spain's electricity production market. The methodology used to achieve these forecasts is based on artificial neural networks, which have been used successfully in many forecasting applications. The days to be forecast include working days as well as weekends and holidays, because energy prices behave differently depending on the kind of day to be forecast. Troncoso Lora et al. (2007) propose a simple methodology based on the weighted nearest neighbours technique to forecast hourly prices in deregulated electricity markets. Forecast results for the market of mainland Spain for the entire year 2002 are reported, with an average monthly error rate of close to 8%. The performance of the method proposed is also compared with that of other techniques such as ANN, Neuro-Fuzzy systems, GARCH, and ARIMA (with and without wavelet transformation).

Goals and contributions

Energy production from RES-E is analysed in this paper, including its direct environmental impacts and its economic implications for the system. Specifically, the idea is to do the following for each of the five main renewable energy technologies and for all of them as a whole:

1. To determine the total value of the subsidies received by each RES-E in 2012.
2. To work out the price reduction generated by the merit order of RES-E in the *pool*. To that end a descriptive model is provided of the process of setting the final price of energy in the *pool* using machine learning techniques (M5P); that model is trialled by following six hypothetical cases that remove each different renewable energy technology from the generation mix, and finally all of them as a whole.
3. To quantify the reduction in emissions of greenhouse and other hazardous gases when generation from fossil-fuelled thermal power plants (coal-fired and Natural Gas Combined Cycle — NGCC) is replaced by generation from RES-E. The life cycle analysis of each technology is analysed accounting for the environmental effects of both power plant construction and O&M during its lifetime. Monetary value to emissions is applied so that all generation alternatives can be compared on a monetary basis.

All this implies that the net cost of RES-E for the system is obtained by subtracting the savings on the energy price and the reduction of pollutant emissions from the subsidies received. This will provide decision-makers in the energy sector with the proper regulations for the development of technologies that on the one hand have less environmental impact and on the other hand represent the best option in economic terms. This becomes even more important when it is taken into account that a full restructuring of the Spanish electric system, and thus of its economic support for RES-E, is currently under way.

Finally, following the same methodology used for the real scenario, for the very first time two hypothetical scenarios are presented and analysed which modify the integration of coal and NGCC in the generation mix.

It is worth noting that the aforementioned merit order effect refers to the current and/or short-term situation where back-up facilities (coal-fired and NGCC) are already built. The large-scale integration of renewable energies into the generation mix has dramatically affected the economic feasibility of NGCC power plants, which have gone from being the basis of the load curve (32.6% of total generation in 2008 — REE, 2013a,b) to playing a secondary role as backup plants in peak demand times and periods of low renewable energy production (14.4% of total generation in 2012 — REE, 2013a,b). Regarding coal-fired facilities, they have gone from representing the 37.2% of the total generation in 2002 (REE, 2003) to 20.4% (REE, 2013a,b) ten years later. As there is no economic incentive to build and set in motion new backup plants, the system itself will therefore have to address that need, this would definitely be a new cost for the system that would therefore being transferred to the electricity prices. Several authors have dealt with this subject in the international environment, e.g., Green and Vasilakos (2011) and Mount et al. (2012), among others and this paper does not seek to quantify the implications of RES-E for the economic feasibility of conventional power plants, already analysed for the Spanish case for Moreno and Martínez-Val, 2011; neither the Capacity Remuneration Mechanism for back-up plants (currently undergoing a review process in Spain) that deserves further analyses when review process ends, not affecting 2012, year studied in the paper.

Material and methods

An explanation is given below of the methodology used to establish:

1. The direct economic impact of renewables on the system due to the subsidies that they receive;
2. The reduction in the final price on the spot market thanks to the merit order of renewables in the electricity auction;
3. An economic assessment of emissions of pollutant and hazardous gases due to the substitution of generation from conventional fossil-fuelled power plants (coal and NGCC) by RES-E.

Direct economic impact: feed-in tariffs

Before the implementation of Royal Decree 19/2013, the installation of a new renewable energy power plant was governed by Special Regime which granted them with a subsidy to make it competitive with conventional generation sources. As a general basis, Special Regime facilities had the chance to receive a fixed tariff (i.e., a flat-rate value that includes an estimated settling market price and a subsidy) or directly receive the settled market price at each specific hour and a fixed specified subsidy. The total tariff under the second approach is forced to be between a cap and a floor. PV facilities were forced from the very beginning to be under the first approach, and all facilities, no matter the technology, were forced to do so after Royal Decree-Law 2/2013 became applicable. The ultimate objective of these subsidies was to encourage significant RES-E deployment that would produce decreases in the cost of generation from renewable technologies so as to make them profitable in a free market in the near future (i.e., with no subsidies). Subsidies received by the five main renewable technologies were as follows: wind power €2.037 bn, photovoltaic €2.6107 bn, biomass €344 M, solar thermoelectric €926.9 M and mini-hydroelectric €184.1 M (CNE, 2013), i.e.,wind power 42.48€/MWh, photovoltaics 321.1 €/MWh, biomass 82.1€/MWh, solar thermoelectric 270.1€/MWh and mini-hydroelectric 40.2€/MWh.

Indirect economic impact: merit order effect

In order to determine the impact of renewables on the final wholesale price of electricity, a descriptive model is generated which simulates final prices on the Spanish spot market. The influence of the main actors involved in the spot market is determined by means of that model. Computational techniques are needed due to the complexity of the electricity system. Unlike the papers shown in the literature review section, in this case, the intention is not to generate a predictive model (ex-ante analysis) but a descriptive model (ex-post analysis) that quantifies the extent to which each attribute affects the final price in the auction. Decision trees based on the M5P algorithm are used (developed by Quinlan, 1992 and improved by Wang and Witten, 1997).

The training data base consists of 8760 instances. Each instance consists of the hourly wholesale electricity price (OMIE, 2013) as well as 23 variables that the former depends on (REE, 2013b). Taking into account that a high number of variables – some have a minimal influence on the market – could lead to an over-training of the model, a preprocessing stage is introduced to determine the attributes most suitable for describing the process. The *BestFirst* search method is used (Rich and Knight, 1991), with *WrapperSubsetEval* (Kohavi and John, 1997) to assess the quality of the attribute by means of a learning algorithm, in this case M5P. After pre-processing, the final variables are:

- Total generation (GWh).
- Generation from hydroelectric power plants (GWh).
- Generation from nuclear plants (GWh).
- Generation from coal-fired thermal power plants (GWh).

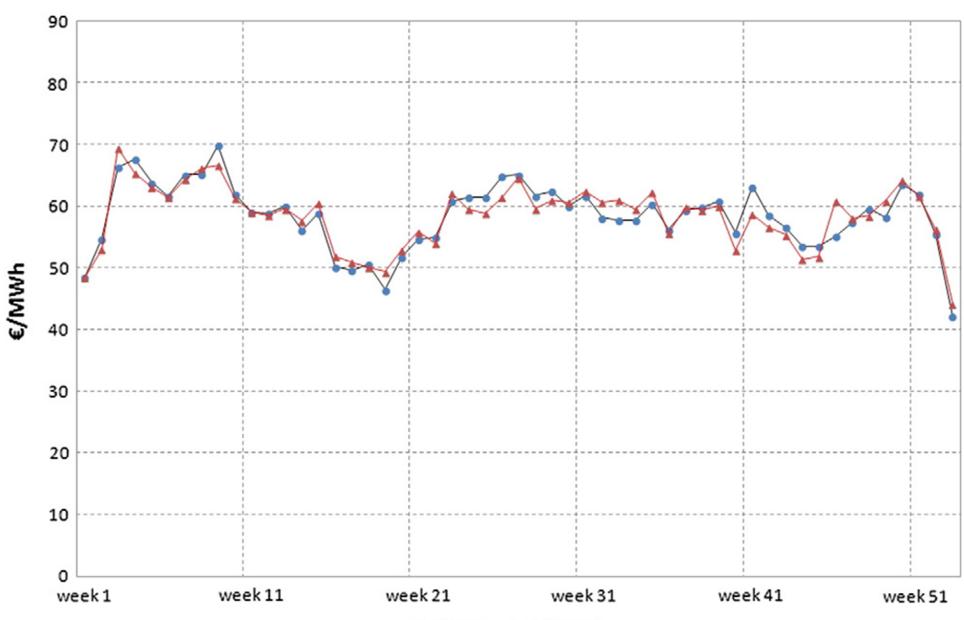

Fig. 1. Comparison of the (weekly production weighted) final average price of electricity in the *pool* (actual) and that obtained for the model generated from the M5P algorithm (predicted).

- Generation from NGCC thermal power plants (GWh).
- Available capacity from nuclear power plants (GW).
- Available capacity from NGCC thermal power plants (GW).

In this way, the M5P algorithm is applied to the hourly data (8760 instances) from 2012 of the aforementioned variables (REE, 2013b). The algorithm is launched with WEKA software (Witten and Frank, 2005).

The M5P algorithm implements routines for generating an M5 model that is used for numerical analysis. The model generated acquires a tree-type distribution where every leaf node has an MLR structure (multiple linear regressions) that predicts the class value of instances that result in a leaf. A non-linear response is obtained by combining all multi-linear regressions.

The tree model “grows” by determining which attribute best splits the portion *T* of the instances that reach a particular node. The standard deviation (SD) of the class in *T* is used as the error at that node and the attribute chosen for splitting is intended to maximise the expected error reduction at that node. The standard deviation reduction (SDR) is calculated as:

$$SDR = sd(T) - \sum \frac{|T_i|}{T} \cdot sd(T_i) \tag{1}$$

where T_i refers to the sets that result from splitting the node.

The splitting routine ends when the SD is lower than the SD of the original instance set or when the minimum allowed number of instances in a leaf node is reached (100 for this case).

The model accuracy is determined by testing the model for the unseen cases (test set). In this way, the relevance of using a cross validation technique instead of the holdout method is highlighted. The holdout method consists of dividing the starting data into independent subgroups: the training set subgroup, to obtain the model; and the test set subgroup, used for the validation process. Taking into account that the model is adjusted on the training set subgroup, the assessment may depend highly on the way in which the subgroups are divided. This led us to use the concept of cross validation instead. In the cross validation of k instances (10 in this case), the sample data are divided into k subgroups. One of the subgroups is used as a test set and the rest ($k - 1$) as a training set. The process of cross validation is repeated over k instances, taking a new subgroup as the test data for each instance.

Finally, the arithmetic mean of the results is calculated to obtain a single result. This method is much more precise than the holdout method as the evaluation uses *k* training sets.

Fig. 1 shows how the model matches the real case. Regarding the parameters related to the model, the Correlation Coefficient (CORR) obtained is 0.85 with a Mean Absolute Error (MAE) of 5.72 and a Root Mean Square Error (RMSE) of 7.70. Based on those figures, it is considered as properly and accurately adapted to the real case and it can thus be used to determine the new prices of energy in the different alternative generation cases and scenarios for 2012. The theoretical formulation of the parameters analysed is shown below.

$$MAE = \frac{1}{n} \cdot \sum_{k=1}^{n} |p_k - a_k| \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (p_k - a_k)^2} \tag{3}$$

$$CORR = \frac{\sum_{k=1}^{n} \frac{(p_k - \overline{p}) \cdot (a_k - \overline{a})}{n-1}}{\sqrt{\sum_{k=1}^{n} \frac{(p_k - \overline{p})^2}{n-1} \cdot \sum_{k=1}^{n} \frac{(a_k - \overline{a})^2}{n-1}}} \tag{4}$$

where *p* and *a* are, respectively, the predicted and actual outputs and *n* is the number of points from the database used to validate the models.

Quantification and economic assessment of CO_2, NO_x and SO_2 emissions

Emission rates are estimated and a monetary value is assigned so that environmental impacts can be included in the overall economic analysis of each technology. The pollutants emitted by each technology in generating 1 kWh are quantified (see Table 2).

The figures for coal and natural gas were obtained with the Simapro tool and its Ecoinvent® database, PRé Consultants (2013). Those for wind power, photovoltaics, biomass and small hydroelectric power are from Akhgari and Kalaman (2013) and solar–thermal power from Pehnt (2006). It is worth noting that the unit values presented in Table 1 take into account not only the direct emissions in the generation of electricity but also the emissions generated during the manufacturing process of the generation plant, O&M work and closure.

Once this is done, the total emissions of a particular generation mix are determined by adding up the unit values of each technology with its assigned share of production within the mix. The total emissions of each pollutant gas are multiplied by its assigned unit cost so that the environmental and economic impacts can be compared.

For the purposes of this paper an average value of \$10/t CO_2 (Akhgari and Kalaman, 2013) is considered for the quotas assigned free of charge to the energy sector. This figure is converted to euros at the average exchange rate for 2012, i.e., €0.8/\$.

For the economic quantification of NO_x and SO_2 emissions unit costs of €480 and €1460/t are set for NO_X and SO_2 respectively (Akhgari and Kalaman, 2013).

Scenarios analysed

Baseline scenario

Now that the descriptive model of the *pool* has been generated and the methodology for quantifying and assessing pollutant gas emissions economically has been set up, the next step is to present the cases to be studied. Six hypothetical cases are presented, one each referring to the five renewable technologies analysed and the sixth taking them all as a whole:

- Case A — real generation mix excluding generation with wind power technology.
- Case B — real generation mix excluding generation with photovoltaics.
- Case C — real generation mix excluding generation with biomass.
- Case D — real generation mix excluding generation with solar–thermoelectric facilities.
- Case E — real generation mix excluding generation with small hydroelectric plants.
- Case F — real generation mix excluding generation with renewable technologies eligible for subsidies (wind power, photovoltaics, biomass, solar–thermoelectric and small hydroelectric — referred as RES-E along the document).

Table 2
Assessment of emission unit values of the electrical generation sources.

	CO_2 [gCO_2/kWh]	NO_x [gNO_x/kWh]	SO_2 [gSO_2/kWh]
Wind power (Akhgari and Kalaman, 2013)	9	0.04	0.055
Photovoltaic power (Akhgari and Kalaman, 2013)	50	0.24	0.27
Biomass power (Akhgari and Kalaman, 2013)	62.5	2.72	0.445
Solar–thermal power (Pehnt, 2006)	13.4	0.0729	0.0467
Small hydroelectric power (Akhgari and Kalaman, 2013)	24	0.07	0.03
Coal (Simapro® — Ecoinvent 2.0)	1090	5.26	11.5
NGCC (Simapro® — Ecoinvent 2.0)	514	0.667	0.314

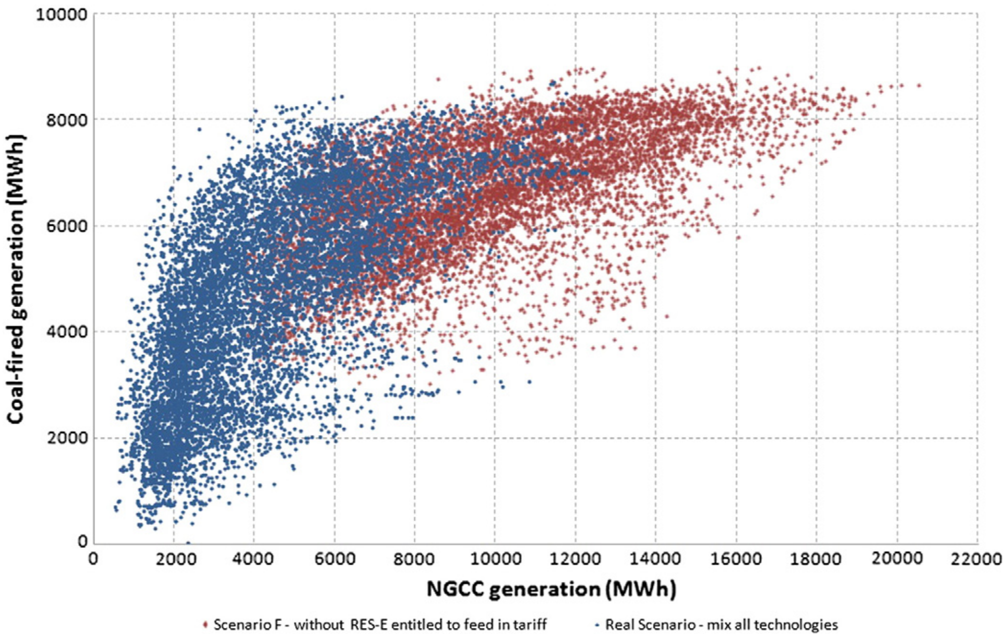

Fig. 2. Comparison between coal-fired and NGCC power generation for the real scenario and a hypothetic scenario without subsidised renewable energy generation (scenario F). The shortfall in power generation from renewables is taken up by backup power plants according to the logarithmic trend observed in the real case in 2012.

The results for these six cases are compared with the real generation mix for 2012 to determine the influence in economic terms of each renewable technology and of all them as a whole on the Spanish power grid.

The premise followed is that energy must be supplied under conditions that guarantee no blackouts, shortages or flaws in the process. To that end, any hypothetical generation gaps in the aforementioned cases must be covered by the so-called backup plants. In the case of the Spanish power grid, these backup plants are fossil-fuelled thermal power plants (coal and NGCC) due, on the one hand, to their installed capacity and low operating hours; and on the other hand to their capability to respond effectively to changes in the system load. Simple Cycle Combustion turbines and others fossil-fuelled technologies represent a negligible percentage on the Spanish electric system.

Finally, the allocation of additional load on coal and NGCC plants, resulting from the removal of a renewable technology from the grid, is determined as follows. A comparative graph of the dispersion of production per hour of coal and NGCC plants in 2012 shows a logarithmic trend. Accordingly, six logarithmic equations are established so that the increase in production from coal and NGCC plants for every hour follows the trend in the logarithmic equation with the best fit. Fig. 2 shows the ratio of generation with coal and NGCC plants in the real scenario and in the hypothetic one without subsided generation form renewables (Case F).

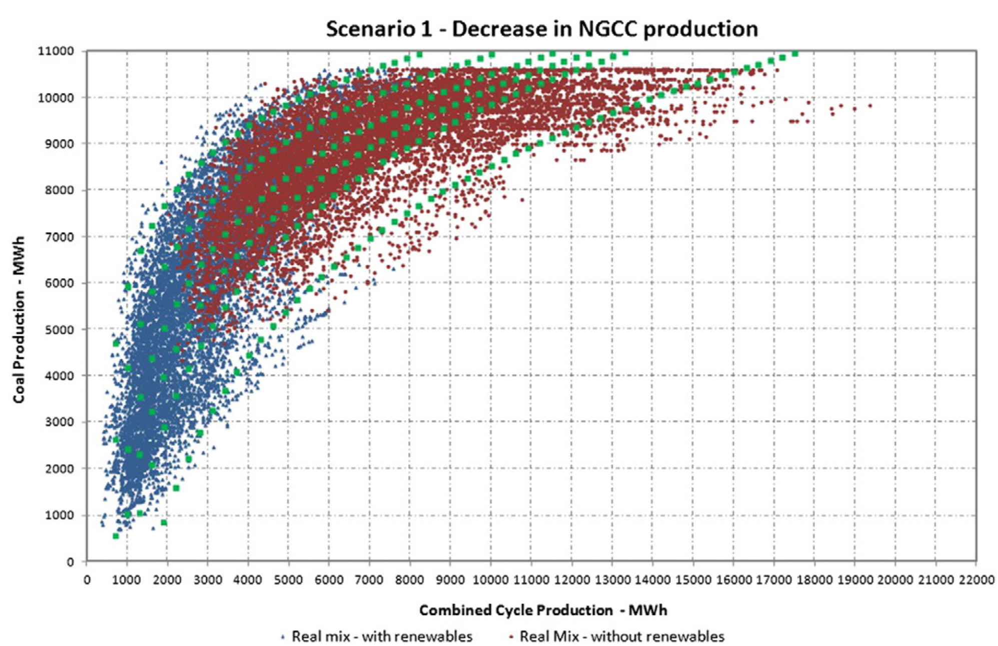

Fig. 3. Comparison between coal-fired and NGCC power generation in 2012 under a supposed 30% reduction in generation from NGCC plants. Scenario 1: each point of the blue series (scenario with subsidised generation from renewables) is displaced along the slope of the logarithmic curve with the smallest error, and the red series is obtained (scenario without subsidised generation from renewables).

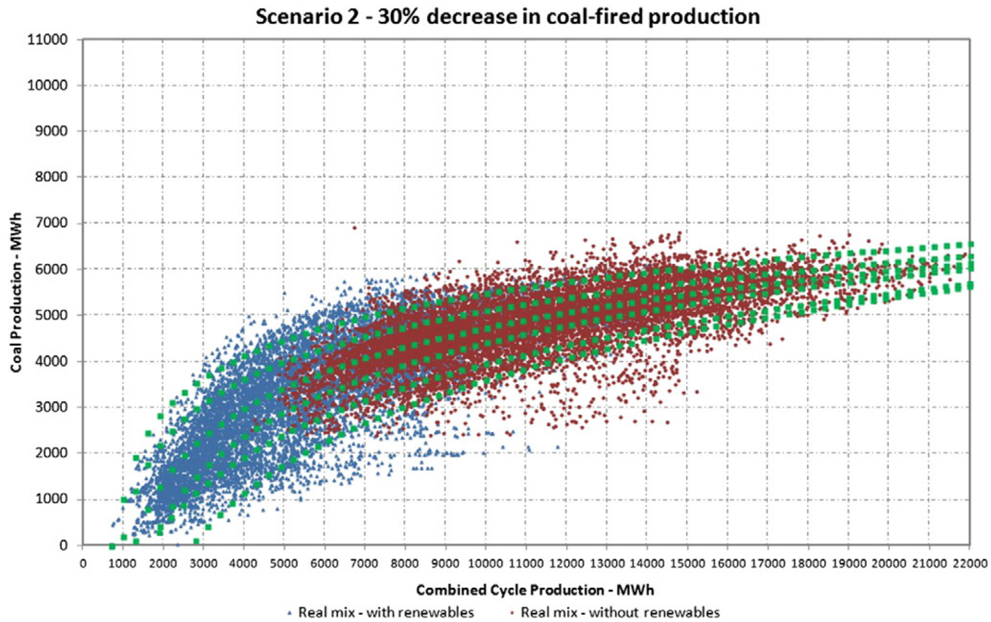

Fig. 4. Comparison between coal-fired and NGCC power generation in 2012 under a supposed 30% reduction in coal-fired generation. Scenario 2: each point of the blue series (scenario with subsidised generation from renewables) is displaced along the slope of the logarithmic curve with the smallest error, and the red series is obtained (scenario without subsidised generation from renewables).

Two assumptions are made. Production in hydroelectric plants in 2012 is considered to be fully optimised to coincide with high demand periods in order to get the greatest profit. Therefore, notwithstanding the fact that they are capable of responding to changes in the system load, they are not intended to operate as back up plants. Second, demand is assumed to not vary with price over the range of price variations considered in this study.

Alternative scenarios

Alternative scenario 1: problems with the supply of imported gas. Major investment in NGCC since 2001 has modified the domestic generation mix and has significantly boosted gas consumption for power generation purposes. However, Spain does not have domestic natural gas (CNE, 2012): gas is imported mainly from Algeria (42%), Nigeria (15.4%) and Norway (11%). Second, the country's capacity for storing natural gas is very low, which means that supplies to power plants are totally dependent on decisions made in other countries. An example of this is the Medgaz project, an undersea gas pipeline from Algeria to Europe which runs through Spain, with an initial capacity of 8 billion m^3 a year (MEDGAZ, 2014). Despite the strategic character of this gas pipeline, Spain, through Natural Fenosa, only owns 15% of the pipeline: the rest of the capital is non-European, from Sonatrach (43% Algeria), and Cepsa (42% Arab Emirates).

In order to reduce dependence on North Africa, the idea is to strengthen the gas interconnection with France, which will enable the

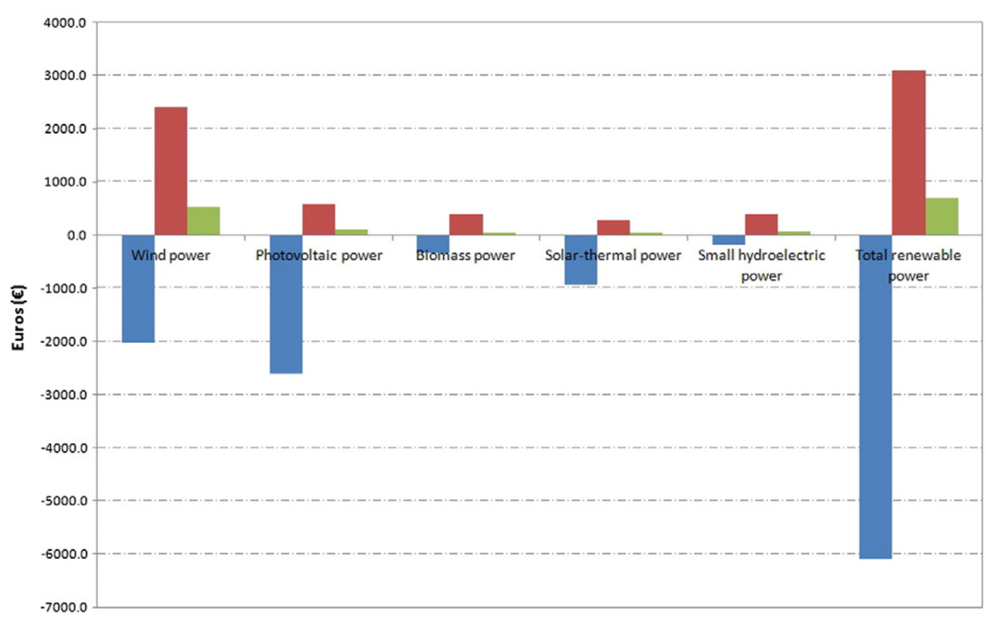

Fig. 5. Net economic influence of renewable energies on the Spanish power system. Actual situation in 2012.

Table 3
Assessment of emissions avoided for each renewable energy technology. Base scenario for 2012.

	TWh	MMT CO_2	MMT NO_x	MMT SO_2
Wind power	48.1	30.14	0.09	0.16
Photovoltaic power	7.8	5.43	0.02	0.03
Biomass power	4.7	3.16	0.00	0.02
Solar–thermal power	3.4	2.58	0.01	0.01
Small hydroelectric power	4.6	3.14	0.01	0.02
Total	68.6	42.61	0.11	0.21

transit of gas between Spain and the rest of Europe to be developed, thus increasing competition between gas suppliers (Algeria, Norway and Russia), improving the use of infrastructures and integrating the Spanish market into the rest of Europe. However, taking into account the current international situation in North Africa, it seems reasonable to consider a potential increase in gas prices which would cause a decrease in generation from NGCC.

To simulate hypothetical supply problems in foreign gas, a scenario with a 30% reduction in generation from NGCC is generated. This shortfall is taken up by the rest of technologies in order to avoid outages on the power supply. Nuclear facilities present a practically constant generation that is not affected by power demand. In the Spanish electric system, RES-E and the rest of the technologies covered under the special regime are producing at maximum power (considering natural resources availability and O&M shutdowns) all the time, only being force to shutdown at very rare occasions that can be considered negligible. Finally, the following assumption is made: large hydroelectric facilities are fully optimised not being intended to operate as back-up plants. Therefore, none of the remaining technologies but coal-fired technology is capable of taking up the shortfall produced by NGCC generation fall. This assumption is presented in the scientific literature. The new ratio of coal-fired to NGCC power plants in this scenario (see Fig. 3 — blue series) is standardised by means of six logarithmic equations. This enables a calculation of the share that is taken by coal and NGCC in a hypothetical scenario in which there are not only gas supply problems but subsidised renewable technologies have been eliminated from the generation mix. Coal and NGCC generation in the scenario without renewables is also moved up and to the right (see Fig. 3).

Alternative scenario 2: stoppages in the domestic mining industry. Domestic coal deposits are Spain's sole fossil fuel reserve for electricity generation; coal thus has a high strategic value in terms of reducing dependence on foreign energy and therefore lower exposure to geopolitical risks. However, the drop in electricity demand in the past two years is making it difficult to use domestic coal, so that coal plants and, by extension, Spanish mines, are under serious threat of immediate closure. That is the reason why Spain has established the Mechanism for Solving Restrictions and Guaranteeing Supply that predicts the withdrawal for some plants in certain conditions, and the use of domestic coal. However, in 2012 subsidies for domestic production of coal were significantly reduced. Along with the recession and short and long-term uncertainty, this led to strikes and stoppages in the sector.

Table 4
Emission savings per technology and pollutant gas. Base scenario for 2012. Average exchange rate for 2012: €0.8/$. Economic quantification of emissions: €8/t CO_2, €480/t NO_x and €1460/t SO_2.

	CO_2 [M€]	NO_x [M€]	SO_2 [M€]
Wind power	241.1	43.0	236.4
Photovoltaic power	43.4	7.5	42.9
Biomass power	25.3	−0.8	27.9
Solar–thermal power	20.6	3.8	21.8
Small hydroelectric power	25.1	5.0	29.2
Total	340.8	51.4	306.2

Table 5
Net economic impact of RES-E on the Spanish electrical system. Base scenario for 2012. Average exchange rate for 2012: €0.8/$.

	Subsides [M€]	Energy price savings [M€]	Emission savings [M€]	Net balance [M€]
Wind power	−2037.0	2401.0	520.5	884.5
Photovoltaic power	−2610.7	576.6	93.8	−1940.3
Biomass power	−344.0	394.7	52.3	103.0
Solar–thermal power	−926.9	278.7	46.2	−602.0
Small hydroelectric power	−184.1	384.7	59.2	259.8
Total	−6102.7	3102.0	698.5	−2302.2

In this way, despite the introduction of the "Regulatory Framework for Coal Mining and Mining Regions in the Period 2013–2018" on October 1st 2013, there is still major uncertainty in the domestic coal sector for future years, especially from 2018 onward (the date set by the European Union for companies that have received financial aid to be closed down or to pay back that aid). On that basis, it is interesting, therefore, to consider a scenario in which coal-fired power generation is decreased by 30%. Since outages on the power supply are not accepted, this shortfall is taken up by NGCC backup plants following the same approach presented in previous section for scenario 1. The new ratio of coal-fired to NGCC power plants in this scenario (see Fig. 4 — blue series) is standardised by means of six logarithmic equations. This enables the recalculation of the share that is taken by coal and NGCC in a hypothetical scenario in which there are not only coal supply problems but subsidised renewable technologies are eliminated from the generation mix. Coal and NGCC generation in the scenario without renewables is also moved up and to the right (see Fig. 4).

Results and discussion

Baseline scenario

The total emissions in each of the cases analysed are obtained by multiplying the unit emissions (g/kWh) by the total generation from each technology (kWh). Therefore, the emissions avoided for each renewable energy technology (see Table 3) can be obtained by subtracting the emissions from the total emissions from the actual generation mix for 2012 (i.e., the emissions avoided by wind power generation are obtained by subtracting the emissions in case A from the total emissions in reality). Table 4 presents the emissions avoided for technology from a monetary side.

Finally, Tables 5 and Fig. 5 show the economic impact of renewables on the system. The subsidies received, the merit order effect and the economic assessment of the emissions avoided by the relevant technologies are taken into account. In the light of the results obtained, the following conclusions are presented:

- Wind power, small hydroelectric and biomass technologies produced a net benefit for the system in 2012 of €884.5, 259.8 and 103.0 M respectively.
- Solar photovoltaic and solar thermoelectric technologies caused a net cost to the system in 2012 of €1940.3 and 602.0 M respectively.
- The five main renewable energy technologies altogether caused a cost overrun to the system of €2302.2 M in 2012.

Table 6
Assessment of emissions avoided for RES-E for base scenario and alternative scenarios 1 and 2.

	MMT CO_2	MMT NO_x	MMT SO_2
Base scenario — total	42.61	0.11	0.21
Scenario 1 — total	47.78	0.15	0.31
Scenario 2 — total	40.47	0.09	0.17

Table 7
Net economic impact of RES-E on the Spanish electrical system for base scenario and alternative scenarios 1 and 2. Average exchange rate for 2012: €0.8/$.

	Subsides [€]	Energy price savings [€]	Emission savings [€]	Net balance [€]
Base scenario — total	−6102.7	3102.0	698.5	−2302.2
Scenario 1 — total	−6102.7	3202.4	906.4	−1993.9
Scenario 2 — total	−6102.7	2853.6	612.8	−2636.3

It is noteworthy that the sum of the values obtained in Tables 1 and 2 for each technology alone does not coincide with the value obtained for them as a whole. This is because independent cases are considered that eliminate each renewable technology from the generation mix respectively, and because of a non-linear response in the case study.

Alternative scenarios

Table 6 shows the reduction in CO_2, NO_x and SO_2 emissions generated by renewables for the baseline scenario and for the two alternative scenarios. The first alternative scenario refers to problems in foreign gas supplies, and the second to a reduction in generation from coal due to regulatory changes in the mining industry.

Finally, Table 7 shows the economic influence of renewables on the system. As in the Baseline scenario section the subsidies received, the merit order effect and the economic assessment of the emissions avoided in each scenario are taken into account. In the light of the results, the following conclusions are presented:

- In a hypothetical scenario with a 30% reduction in power generation from NGCC plants (to be covered by coal-fired backup plants), renewable energies would have saved the system €3202.4 M in the energy auction and €906.4 M in terms of the financial quantification of the reduction in pollutant gas emissions. Taking into account the subsidies received, their net cost would be €1993.9 M.
- In a hypothetical scenario with a 30% reduction in coal-fired power generation (to be covered by NGCC power plants), renewable energies would have saved the system €2853.6 M in the energy auction and €612.8 M in terms of the financial quantification of pollutant gas emissions. Taking into account the subsidies received, their net influence would have been a cost to the system of €2636.3 M.
- Sensitivity analysis shows a similar financial influence of renewable energies in the three scenarios studied (baseline scenario and two alternative scenarios). The cost overrun is slightly higher in scenario 2 (€2636.3 M) and slightly lower in scenario 1 (€1993.9 M) than the real case (€2302.2 M).

Conclusions and policy implications

The paper concludes that the five main renewable technologies in the special regime avoided the emission of 42.61 MMT of CO_2, 0.11 MMT of NO_x and 0.21 MMT of SO_2 with a value of €698.5 M, received subsidies of €6102.7 M and resulted in a saving in energy auctions of €3102.0 M. Accounting for all these points, the five main RES-E together represented a cost of €2302.2 M in 2012. However not all technologies have the same effect on the system. Wind power, biomass and small hydroelectric technologies are profitable, while photovoltaic and solar thermal power technologies give rise to deficits. The general recommendation at that time for these last two technologies is that they were not yet technologically mature, so investment in large-scale generation was not advisable in their case, but rather in direct R&D + i policies. However, it has been demonstrated that other technologies (wind power, biomass and small hydroelectric) had reached high levels of maturity in their cost curve, which made them competitive in the system with low levels of premiums, and profitable if the emissions that they avoid and the price reduction that they produce are taken into account. In this complex situation, Spain should reconsider its energy outlook and assess the role that can be assigned to each power source, so that a compromise is reached between environmental quality and the struggle against climate change, energy supply security and economic competitiveness.

Taking into account Spain's dependence on foreign natural gas and the political tensions in the Spanish mining industry, the influence of renewables on the system is also studied in terms of possible contingencies in supplies from coal-fired and NGCC power plants. The findings, which give figures of between 87% and 115% of the original levels, make the contributions of the paper as a whole more robust. We believe that the authorities must make decisions in the medium–long term, so potential eventualities and risks need to be taken into account and properly assessed.

References

Akhgari PA, Kalaman H. Economical–environmental evaluation of natural gas and renewable energy systems. Int J Energy Res 2013;37(12):1550–61.

Azofra D, Martínez E, Jiménez E, Blanco J, Saenz-Díez JC. Comparison of the influence of biomass, solar–thermal and small hydroelectric power on the Spanish electricity prices by means of artificial intelligence techniques. Appl Energy 2014;121:28–37.

Burgos-Payán M, Roldán-Fernández JM, Trigo-García TL, Bermúdez-Ríos JM, Riquelme-Santos JM. Costs and benefits of the renewable production of electricity in Spain. Energy Policy 2013;56:259–70.

CNE Comisión Nacional de Energía / Spanish Energy Commission. Supervisión de los abastecimientos de gas y la diversificación de suministro (Monitoring of supply and diversification of gas supply). ; 2012 [December].

CNE, Comisión Nacional de Energía / Spanish Energy Commission. Informe sobre los resultados de la liquidación de las primas equivalentes, primas, incentivos y complementos a las instalaciones de producción de energía eléctrica en régimen especial. Mes de producción 12/2012 / (Report on the results of the liquidation of bonuses and equivalent bonuses, incentives, and complements to the production facilities of electricity in special regime. Production Month 12/2012). ; 2013.

Cruz A, Muñoz A, Zamora JL, Espínola R. The effect of wind generation and weekday on Spanish electricity spot price forecasting. Electr Power Syst Res 2011;81(10): 1924–35.

Forrest S, MacGill I. Assessing the impact of wind generation on wholesale prices and generator dispatch in the Australian National Electricity Market. Energy Policy 2013;59: 120–32.

Gelabert L, Labandeira X, Linares P. An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. Energy Econ 2012;33(1):59–65.

Gil H, Gomez-Quiles C, Riquelme J. Large-scale wind power integration and wholesale electricity trading benefits: estimation via an ex post approach. Energy Policy 2012; 41:849–59.

Green R, Vasilakos N. The long-term impact of wind power on electricity prices and generation capacity. University of Birmingham Economics Discussion Paper 11-09; 2011.

Kohavi R, John G. Wrappers for feature subset selection. Artif Intell 1997;97(1-2): 273–324.

McConnell D, Hearps P, Eales D, Sandiford M, Dunn R, Wright M, et al. Retrospective modeling of the merit-order effect on wholesale electricity prices from distributed photovoltaic generation in the Australian National Electricity Market. Energy Policy 2013;58:17–27.

MEDGAZ. Company to study and build the Algerian–European gas pipeline via Spain, S.A. http://www.medgaz.es, 2014. [Accessed January 2014].

Moreno F, Martínez-Val JM. Collateral effects of renewable energies deployment in Spain: impact on thermal power plants performance and management. Energy Policy 2011; 39:6561–74.

Mount TD, Maneevitjit S, Lamadrid AJ, Zimmerman RD, Thomas RJ. The hidden system costs of wind generation in a deregulated electricity market. Energy J 2012;33(1): 161–86.

NOAA, National Oceanic Atmospheric Administration. http://www.noaa.gov, 2014. [Accessed January 2014].

OMIE, Operador Mercado Ibérico de la Energía/ Iberian Energy Operator. Information available online. http://www.omel.es, 2013. [Accessed February 2013].

Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew Energy 2006;31:55–71.

Pino R, Parreno J, Gomez A, Priore P. Forecasting next-day price of electricity in the Spanish energy market using artificial neural networks. Eng Appl Artif Intel 2008; 21(1):53–62.

PRé Consultants. SimaPro database manual. Methods library. Amersfoort: PRé Consultants; 2013.

Quinlan RJ. Learning with continuous classes. 5th Australian Joint Conference on Artificial Intelligence, Singapore; 1992. p. 343–8.
REE, Red Eléctrica de España / Spanish Electrical Grid. Informe del Sistema Eléctrico español 2002 (The Spanish Electricity System. Report 2002). ; 2003.
REE, Red Eléctrica de España / Spanish Electrical Grid. Informe del Sistema Eléctrico español 2012 (The Spanish Electricity System. Report 2012). ; 2013a.
REE, Red Eléctrica de España / Spanish Electrical Grid. Information available online. http://www.ree.es, 2013. [Accessed February 2013].
Rich E, Knight K. Artificial intelligence. McGraw-Hill; 1991.
Sáenz de Miera G, del Río González P, Vizcaíno I. Analysing the impact of renewable electricity support schemes on power prices: the case of wind electricity in Spain. Energy Policy 2008;36(9):3345–59.
Sensfuß F, Ragwitz M, Genoese M. The merit-order effect: a detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 2008;36(8):3076–84.
Troncoso Lora A, Riquelme Santos JM, Gómez Expósito A, Martínez Ramos JL, Riquelme Santos JC. Electricity market price forecasting based on weighted nearest neighbors techniques. IEEE Trans Power Syst 2007;22(3):1294–301.
Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew Sustain Energy Rev 2013; 28:555–65.
Wang Y, Witten IH. Induction of model trees for predicting continuous classes. Proceeding ECML '97 Proceedings of the 9th European Conference on Machine Learning. London, UK: Springer-Verlag; 1997.
Weigt H. Germany's wind energy: the potential for fossil capacity replacement and cost saving. Appl Energy 2009;86(10):1857–63.
Witten IH, Frank E. Data mining: practical machine learning tools and techniques with Java implementations. San Francisco: Morgan Kaufmann; 2005.