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The Green Game Changer: An Empirical Assessment of the Effects of Wind and Solar Power on the Merit Order

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August 2013

Abstract

We estimate the impact of renewable energy sources on the merit order and the wholesale price in Spain. We use a structural vector-autoregressive model for the merit order of production and argue that wind and solar production are exogenous to the system. As expected the overall effect is negative for the wholesale price and the produced quantities of most generation technologies. The estimated impact, however, is biggest for mid-merit plants. This finding sheds light on the theoretical discussion about which power plants are affected most by renewable energy sources. The effect is also mainly driven by wind power. Solar energy increases wholesale prices as peak plants enlarge their production with more solar power.

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1 Introduction

European power markets are in transition towards a system based on low carbon generation. Before the introduction of renewable energy sources (RES), the generation mix of most countries consisted mainly of plants using coal, gas, oil, hydro or uranium as primary source of energy. All of which are able to deliver power at a stable and reliable rate. The increasing public awareness on ecological issues, particularly the reduction of CO_2 emissions, forces power production to become greener and more sustainable. Regulatory measures have been introduced to influence the choice of the primary energy resource.

Two types of policies set the stage for this more eco-friendly approach in the European electricity sector. The first is the introduction of a tradeable emission certificate system to internalize the cost of pollution, the EU Emissions Trading System (EU-ETS). Secondly, public support-schemes for power generation based on renewable resources have been devised to incentivize the investment in more ecological power production technologies. The European Union support framework sets the goal that at least 20% of the final electricity consumption has to be covered by renewable energy resources by 2020. This analysis focuses on effects of RES generation promoted by out-of-market support schemes on market-based power generation.

Wind and solar radiation are the most prominent renewable energy sources. Along with regulated financial support, power production based on RES usually also benefits from prioritized feed-in, guaranteeing a permanent and secure revenue stream for each produced unit.[1]. This is, operators of wind and solar power plants produce and sell power to the market whenever the wind blows or the sun shines. Even if prioritization were abandoned, near-zero marginal costs would still leave RES generation to be first feed-in, as all other technologies have at least the input costs to bear. Power production from renewables can be considered as an exogenous supply shock to the physical and commercial power system. The power market only has to cover the residual demand which is not already served by RES generation.

As a consequence, conventional power plants have to incorporate the (expected) production of renewables into their production decision. This may have a fundamental impact on the market design and security of supply because it leads to a one-sided competitive relationship between conventional and RES power plants. Both types serve electricity demand but only RES generation creates competitive pressure on conventional power plants, but not vice versa.

The effect of intermittent RES generation on conventional production and on the wholesale price of electricity is called the *merit-order effect*. The merit order of production ranks the available power plants in ascending order according to their marginal costs of production. The plants with the lowest marginal costs deliver power most of the time and are dispatched first. The higher the demand

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[1] Network operators can deny feed-in only for system reliability concerns.

rises, the more expensive plants are utilized. Power price corresponds to the marginal costs of the last power plant that is still needed to cover demand. Power from renewable energy sources with prioritized feed-in and zero marginal costs will always be first to cover demand, leaving the conventional power plants competing for the remaining demand. Since RES production (like wind and solar) is intermittent, it cannot deliver a stable and reliable output because it is highly dependent on weather conditions; hence, it can have different effects on the merit order.

In theory, there is no clear cut answer as to which type of technology will be affected most. On the one hand, demand for power produced by conventional technologies is reduced (called residual demand), thereby reducing the need to fully utilize the existing conventional power plant fleet. The low marginal costs of RES production could therefore replace the most expensive peak plants in the merit order. This would translate into lower power prices. On the other hand, demand for conventional plants is only reduced if the wind is blowing and the sun is shining, i.e. the scale of residual demand crucially depends on the frequency and scale of RES generation. So the second effect of RES on the merit order is caused by inherent unreliability of RES and demand for conventional plants not reduced consistently, but depends on weather conditions. If residual demand is exposed to higher volatility, the same holds for the runtime of conventional power plants. This in turn requires utilization of more flexible power plants, which, however, are also the most expensive plants in the merit order. So depending on the scale and frequency of RES generation feed-in, this can affect mid-merit plants and maybe to some degree baseload plants. The latter would still be needed to cover the steady demand which cannot be covered RES generation and flexible peakload plants would be utilized to balance the fluctuating production of wind and solar power. Consequently, prices drop when RES produces and rise when the more flexible plants are needed. As a result, the average power prices may be higher under a RES regime than without.

We contribute to the current debate about the effects of support schemes for renewable energy resources by using data from the Spanish power market, to estimate the merit-order effect for the years from 2008 to 2012. We show the effect on the quantities sold to the wholesale market by the conventional production technologies during instances when renewable produce. We will also show how this influences the wholesale price. Hence, we take the merit order as the given structure and incorporate it into a structural vectorautoregressive (SVAR) model, i.e. we consider production of conventional power plants and price as endogenous and also take the time structure of the data into account. Wind and solar energy production are regarded as exogenous to the system, which reflects the current market situation with prioritized feed-in and support schemes.

We are able to identify and quantify the effect of wind and solar power generation on the wholesale price and on the quantities produced by each conventional power plant type, separately. This helps to understand how the current and future production mix is affected by the support schemes for renewable sources

The Spanish power market combines several characteristics which makes it very suitable for testing the merit-order effect. Renewable technologies need not compete in the power market as they are promoted through out-of-market support schemes. The energy production mix is made up by a large amount of RES production technologies, particularly wind and solar and the climate on the Iberian peninsula is very favorable for both wind and solar power production. Aside from this, the ample availability of data, especially on the production patterns of the different technologies, makes this analysis possible.

The rest of the chapter is structured as follows: section two provides an introduction to the theory of power markets and the merit-order effect. Section three illustrates the Spanish power market. We then present the data used in section four prior to laying out the empirical strategy. The results are presented in section six. The analysis concludes in section seven.

2 Theoretical Background

To analyze the effects of intermittent production on the composition of the power plant fleet and the market design, we first provide a concise insight of the theoretical background of power markets to explain the merit-order effect. This is fundamental in understanding how non-market based RES production affects the mechanisms in the market, and in determining which conventional generation technologies could be affected most.

2.1 Peak-Load Pricing and the Merit Order of Production

Electricity has special characteristics which distinguishes it from other goods. It is a grid-bound good which is neither storable nor substitutable; its provision has physical limitations and its production has to equal consumption at all times. Furthermore, demand for electricity is periodic, varying substantially during the day and over the seasons of a year. Typically, demand reaches its peak during the working hours of a weekday, but is relatively low during nighttime and on weekends. Depending on the geography and climate conditions, consumption patterns differ from summer to winter.

These features make power markets subject to peak-load pricing.[2] Crew et al. (1995) present a summary of the basic principle of peak-load pricing: Different production technologies are needed to satisfy the fluctuating demand. These technologies differ in marginal and fixed costs. The technology with the lowest marginal costs has the highest fixed costs, while the one with the highest marginal cost has the lowest fixed cost. Hence, technologies can be put in order

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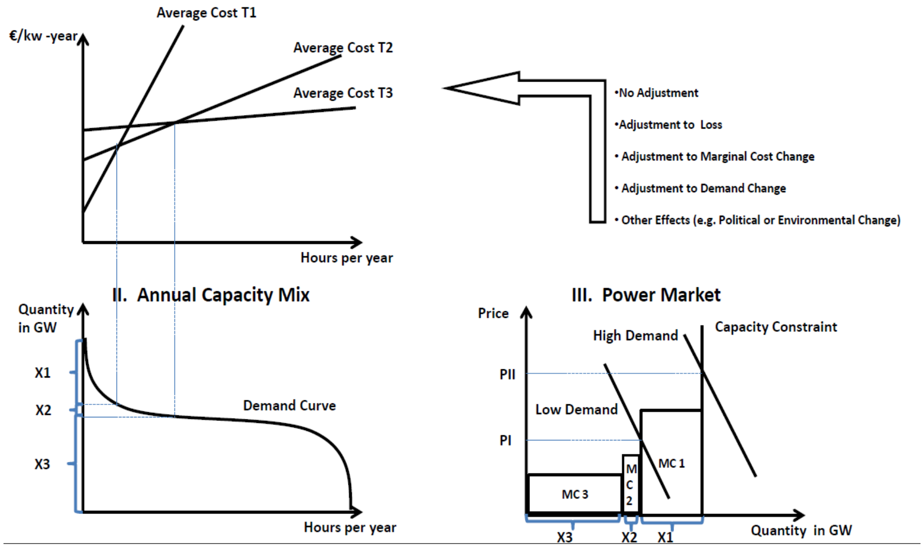
[2] See Boiteaux (1960) and Williamson (1966) for some of the earliest works in this field.

according to their marginal costs. The cheapest technology serves any positive demand up to its capacity. The other technologies therefore, always have idle production capacities whenever demand can be at least partly covered by cheaper technologies. Hence, the price during peak-demand periods has to be such that it enables the most expensive production technologies to recover their variable and fix costs.

Ranking power plants according to their marginal costs is called merit order. In practice, the merit order can be divided into base-, mid-merit and peakload plants. Baseload plants usually consist of hydro, nuclear and lignite power plants, whereas mid-merit plants consist of coal-fired and combined-cycle-combustion gas turbines (CCGT). Peakload plants are usually open-cycle gas turbines or plants fired with oil or gas. A cost overview and a confirmation of the chosen classification can be found in OECD (2010). The report covers the fixed and variable costs of a large set of production technologies and countries.

The merit order is not static, and adjustments in the power plant fleet take place constantly. Aside from the effect of renewable energy resources, various factors also affect the merit order. These adjustments are explained in a stylized example in the following figure.

Figure 1: Static Optimal Capacity Choice and Peak-Load Pricing



Production technologies are labelled as T1, T2 and T3, installed capacities as T1 for X1, T2 for X2 and T3 for X3. Marginal costs of production for technologies T1, T2 and T3 are MC1, MC2 and MC3. PI and PII indicate the equilibrium prices during low and high demand.

An optimal capacity choice is made in a setting of perfect competition, merit order dispatch and a single-price auction. Three production technologies (T1, T2 and T3) are available to market participants. Based on the relationship between average costs and annual expected runtime of each production technology, an optimal plant mix for the provision of power exists. If the relative mixture of technologies is chosen optimally, its adaption to the expected yearly demand distribution yields a specific realization of the actual installed capacities (panel I and II).

Given this capacity choice, market participants bid their available capacities into the market. The optimal bid is the respective marginal cost of the plant, if the level of competition is sufficiently high. Each time overall demand exceeds the individual capacity of a dispatched technology type, profits are generated for this plant type. During these times, plants will recover their annualized investment and fix costs. This creates a specific utilization of the existing production mix and price distribution (panel III).

Depending on this mechanism and factors such as policy changes, adjustments to the current power plant portfolio may become necessary (panel IV). This could lead to temporary or permanent shifts in the technology mix or even the crowding out of plants using certain primary fuels. For instance, a planned or unplanned plant outage is temporary and usually does not lead to a permanent change in the merit order. Changes in the variable costs can lead to either persistent or temporary alterations - so-called fuel switches - depending on the size and frequency of the fluctuations. In the energy market, variable costs mainly consist of fuel costs (input price plus transportation costs), ramping costs and, depending on the technology, costs of emission certificates. Possible fuel switches mostly occur between coal-fired and gas-fired power plants (Sunderkötter and Weber (2011) for a theoretical model and simulation). Persistent changes in the merit order can be caused by advances, such as process innovation or the development of a new production technology. Other reasons can include the depletion of a resource or the general prohibition of its usage (e.g. the nuclear phase-out in Germany).

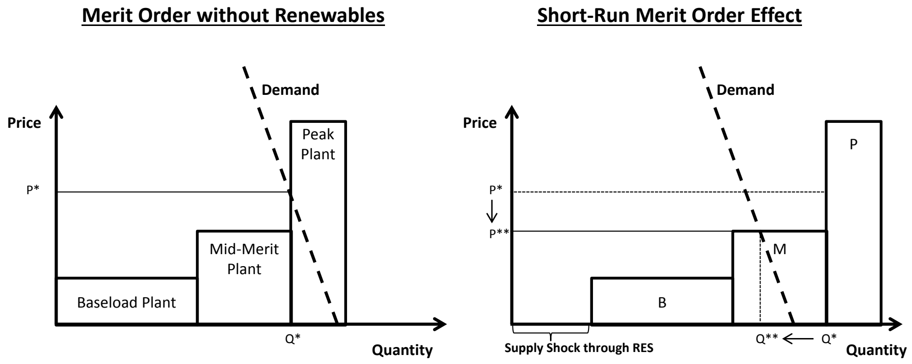
2.2 Merit-Order Effect

The *merit-order effect* describes the effect of weather-dependent (intermittent) renewables on the wholesale power market, particularly on the composition of the plant fleet. The production of the most prominent renewable technologies, wind and solar, is dependent on the availability of wind and sun. As no other input factor is needed for production, the marginal costs are zero or near-zero. Hence, they are located at the leftmost part of the merit order (see Figure 2).

The production decision of renewables is not market based. Investment and feed-in are usually regulated and independent from the market mechanism. To incentivize investment in RES technologies, different support schemes for renewable energies have been developed since the 1990's, varying widely in their character (Haas et al. 2008 and Haas et al. 2004 for an overview). These subsidies can be based on actual generation (per kWh) or on installed capacity. Sometimes also lower interest rates or tax credits are used to stimulate investment (Menanteau et al., 2003 and Haas et al., 2004).

Support schemes can also be divided into price or quantity driven instruments. The former pays a fixed amount independent of the actual production, while the latter seeks to reach a desired level of generation. Most of these support schemes also allow technologies a prioritized feed-in of their generation. Consequently, the compensation of RES technologies is not market-based and the decision to produce or to invest does not depend on the conventional power plants' production decision. Hence, generation by renewables is independent from competition in the power market or from any other economic factors that should be taken into consideration by the conventional power plants. For conventional power plant owners, generation by renewables is an exogenous supply shock and results in a reduction of residual demand.

Figure 2: The Effect of Renewables on the Merit Order



Base, Mid-Merit and Peak refer to the marginal costs of the respective production technology.

The right side of Figure 2 depicts the classical shor-run merit-order effect as described for example by de Miera et al. (2008). Wind and solar power have zero marginal costs and are fed-in first; they shift the merit order to the right. Technologies with the highest marginal cost are crowded out, as they are no longer needed to satisfy demand. In consequence, this decreases the price level as total demand is covered by cheaper technologies. Some empirical studies (such as Green and Vasilakos, 2010; the Spanish Renewable Energy Association, 2009; de Miera et al., 2008; Sensfuss et al., 2008; Gelabert et al., 2011) find evidence of RES production's price decreasing impact.

Yet, in the long-run it could well be that the initially crowded-out peak plants may replace mid-merit plants, which can be seen from Figure 1. The advantage of baseload and mid-merit plants over the flexible but expensive peak plants lies in consecutive runtime hours. High volatility in combination with a large magnitude of RES generation reduces the number of consecutive runtime hours of mid-merit and perhaps even baseload plants significantly, eliminating that very cost adavantage over peak plants. As a result, the lack of runtime and the aforementioned reduction of price peaks may lead to an adjustement in the merit order, e.g. it may collapse to a combination of baseload and peakplants. Vives (1989) shows in a general oligopoly setting that firms tend to invest in more flexible technologies if there is an increase in basic uncertainty. In our context, basic uncertainty is represented by a higher volatility in residual demand, and the shift towards more flexible production implies a shift towards more flexible and expensive plants. A higher volatility of prices would be the result and, depending on the realized distribution of prices, even higher average prices.

Furthermore, the reduced number of price peaks affects all power plants. As the last power plant accepted in the auction to satisfy demand sets the price, all the other power plants to its left in the merit-order earn money on top of their marginal costs. Baseload and mid-merit plants with relatively high fixed costs need a certain amount of high prices during the year and consecutive hours of runtime to cover the fixed costs. If peak load plants leave the market and the price level decreases, the profitability of all power plants in the merit-order would also decrease. Also, the profitability of future investments in the power plant fleet will depend on the price level and will be influenced by this development.

Gelabert et al. (2011) conduct a study of the Spanish power market data. They analyze the effect of the Spanish *Special Regime* - which includes wind, solar, and other renewables, as well as smaller fossil fueled plants - on the wholesale price. They take into account the production of all other power plant types and find a negative price effect of renewables. The magnitude of the price effect, however, decreases over time. The quantity effect on the different production technologies is not considered.

Weigt (2009) could not confirm the crowding out of any specific conventional production technologies. Simulation studies by Bushnell (2011), Delarue et al. (2011) as well as Green and Vasilakos (2010), however, find the suggested switch to more flexible generation types as indicated by Vives (1989).

2.3 Market Design and RES

The merit-order effect also influences security of supply. Sufficient capacity needs to be ready to cover demand at any time. Power markets must provide investment incentives to attract the deployment of new capacities and to allow upgrade of existing plants. As the out-of-market support schemes influence the wholesale price and consequently the price signal to investors, it becomes questionable whether the energy-only market is capable of guaranteeing security of future supply.

Even without renewable energy sources it is unclear whether an energy-only market can attract sufficient investment. Cramton and Stoft (2005, 2006 and

2008) and Joskow and Tirole (2007) argue that the necessary number of high price spikes may not be realized. This so-called missing-money problem can lead to a permanent underprovision of installed capacity. To overcome this problem, it may be necessary to not only reimburse actual power production, but also the provision of capacity.

The increase of renewable power production is likely to intensify the missing-money problem. If either price peaks are cut or the runtime of power plants are reduced, the profitability of conventional power plants decreases. As conventional power plants are still needed to satisfy demand when there is little or no production by wind and solar, a market exit would jeopardize security of supply. Capacity payments can help keep essential plants in the market and attract sufficient further investment. The design of those capacity payments, however, can create other inefficiencies and disincentives (Böckers et al. 2011, in German only).

Another basic task of the market design is the production of cost-efficient energy. Out-of-market support schemes may also lead to inefficiencies in the technology mix. Firstly, not letting the market decide which RES technology to support can lead to an excessive expansion of a certain technology type which is desired by policy makers; this, however, is not the most efficient outcome in terms of achieving climate goals. Secondly, they lead to an adjustment in the remaining power plant fleet, but while the adjustment might be efficient under the prevailing conditions with renewable technologies, the resulting plant portfolio may nevertheless induce further costs.

This section emphasizes that renewables have an impact on the electricity wholesale market in many respects. We empirically analyze which generation technology is affected by RES, and to what extent. Quantifying this effect helps evaluate the market performance, renewable support schemes and the evolution of the security of supply.

3 Spanish Power Market

The Spanish wholesale electricity market consists of a day-ahead market, which is organized as a pool, and a number of intra-day and balancing markets. The pool is designed as a uniform-price auction with the bid of the most expensive power plant needed to satisfy the demand setting the price.[3] Although bilateral trading is possible, the majority of the electricity is bidden into the pool. In the period from 2008-2012, 61%- 69% were traded in the day-ahead market (OMIE, 2013 and REE, 2013a).

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[3] On 1st July 2007 the Spanish and the Portuguese electricity markets were coupled to create the common Iberian electricity market, MIBEL (Mercado Iberico de Electricidad). Only the Spanish system is considered here.

To meet the renewable energy targets set by the Spanish government and the EU, a support framework was established. The Spanish targets comply with the EU's goal of having at least 20% of final electricity consumption covered by renewable energy sources, by 2020 (Moreno and Garcia-Alvarez 2011). The legal promotion of renewable energy sources in Spain was initiated in 1980. The 'Law of the Electricity Sector' implementing the requirements of the European Directive 96/92/EC on the electricity market liberalization also established the *Special Regime.*

The *Special Regime* consists of renewable energy sources, conventional plants with a generation capacity of less than 50 MW and imports. It guarantees green power producers access to the grid as well as monetary support (Law 54/97). Royal Decree 2818 (RD 2818/1998) regulates the treatment of plants in the Special Regime and lays the foundation of the two support system currently in place.

The generators in the *Special Regime* can choose from one of two payment schemes which becomes binding for the following year. They can either opt for a time-dependent feed-in tariff (FIT), where generators receive a fixed total price per MWh fed into the grid, or bidding into the pool and receiving a feed-in premium depending on the market price. If the market price is too low, this so-called cap-and-floor system guarantees producers remuneration at floor level. If the market price exceeds cap level, the producer gets the market price itself. Between the cap and floor levels, the producer receives a premium on top of the market price. Additionally, the support levels in both payment schemes vary according to peak (8 a.m. until 12 p.m.) and off-peak (12 p.m. until 8 a.m.) times.[4]

Conventional power plants including hydro power plants with generation capacities of at least 50 MW are part of the so-called *Ordinary Regime*, and they either bid their power into the pool or trade bilaterally. To stimulate the construction of new production facilities and discourage the retirement of already existing plants, a system of administrative capacity payments was introduced. The so called *pagos for capacidad* was introduced in 2007 and it reformed the system in place since market liberalization. The underlying idea is to support the market mechanism to achieve the desired level of supply security. Depending on the current reserve margin, power plants receive a certain amount per installed MW for the first ten years of operation. The incentive decreases with an increasing reserve margin. If the maximum reserve margin of 30% is reached, the capacity payment will gradually decline to zero (Federico and Vives, 2008).

The generation mix in Spain has changed continuously since the liberalization in 1998 (see Figure 3). While the installed capacities of nuclear, coal and hydro power plants remained constant, those of fuel/gas plants declined over time; however, CCGTs and *Special Regime* installed capacities increased. The latter

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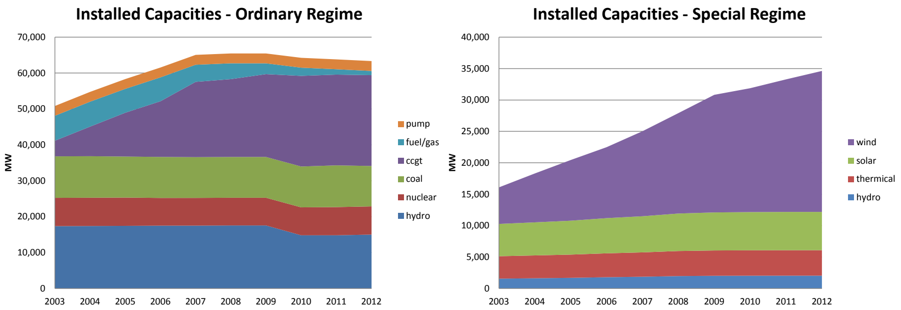
[4] For further information see RD 436/2004, RD661/2007, RD 1578/2008, RD 1565/2010 and RDL 14/2010. Detailed summaries and assessments of the Royal Degrees can be found in del Rio and Gual, 2007; del Rio Gonzalez, 2008 as well as del Rio and Mir-Artigues, 2012.

almost increased sevenfold - from 5,713 MW in 1998 to 38,953 MW in 2011 (Platts 2011), which is about 38% of the total installed capacities (REE 2009, 2013a).

Within the *Special Regime*, wind energy holds the largest share with 54%, but because of a reform in 2004 (RD 436/2004) solar energy production experienced significant growth from 2006 to 2009. In a span of only two years (del Rio and Mir-Artigues, 2012) its installed capacity increased from 300 MW to 3,500 MW. The subsidies for solar generators almost tripled from €2.2 Billion to €6 Billion annually. Solar power producers received 40% of the total payments in the renewable support scheme, but it only accounted for 8% of its generation (Federico, 2011).

Figure 3 shows the development of both the *Ordinary Regime* and the *Special Regime*, in Spain. Hydro appears in both categories because small hydro plants with an installed capacity of less than 50MW are classified as *Special Regime*. CCGT power plants and wind power plants experienced the biggest growth. Note that the two graphs are scaled differently. *Special Regime* has now surpassed half of the installed capacity of the Ordinary Regime.

Figure 3: Installed Capacity for the Ordinary and Special Regime



Source: Platts 2011, REE(2009,2013).

4 Data

We analyze the Spanish power wholesale market from the period of 2008 to 2012. Data on Spanish demand, produced quantities[5] for each conventional fuel-type, i.e. nuclear, hydro, coal and gas, and generation from the *Special Regime* is publicly available. The latter is comprised of the production of solar and wind power, as well as the generation of other renewable and non-renewable

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[5] Gas is subdivided into *cc*, which is a more efficient production type called combined cycle gas turbines, and *fuel/gas*, which includes the most expensive power plants running on either coal or gas.

resources. We are, however, able to separate the *Special-Regime* generation in wind and solar and its other components. Furthermore, we use hourly electricity wholesale prices (OMIE, 2013 and REE, 2013a).

The installed capacities for each generation technology and the respective input prices are included as control variables i.e. prices for oil, gas, coal and uranium and European emission certificates (REE, 2009 and 2013; APX, 2013; Platts, 2011; Argus/McCloskey, 2013; UX Consulting, 2013; IEA, 2013; EEX, 2013). The input prices are available either on a weekly or weekday basis. Installed capacities are available on a yearly basis stated in MW (REE, 2009 and 2013).

Pooling all technologies in the Special Regime includes certain conventional and reliable plants (i.e. power plants with installed capacities of less than 50MW or RES technology such as biomass, which can deliver reliably). From this, we divide the *Special Regime* into its components: wind generation, solar generation and others. For wind data, we use the hourly wind forecast (REE, 2013a) and for solar data, we use the mean daily (actual) solar production[6] (REE, 2013) as there is no publicly available data on hourly solar production. To match the daily production of solar with the hourly data, we aggregate the data set to the daily average.

Table 1: Daily Windforecast and Solar Production

Windforecast					
Variable	Mean	Std. Dev.	Min	Max	Inst. Cap. (MW)
2008	3,555.07	1,890.28	551.18	8,663.24	15,977
2009	4,086.87	2,159.91	597.94	10,471.94	18,712
2010	4,861.05	2,521.63	877.29	13,088.47	19,710
2011	4,736.95	2,572.58	941.53	12,013.12	21,091
2012	5,453.75	2,775.65	1,096.54	13,693.33	22,430
2008-2012	4,538.59	2,490.38	551.18	13,693.33	19,583 (Mean)
Solar production					
Year	Mean	Std. Dev.	Min	Max	Inst. Cap. (MW)
2008	275.05	135.39	83.33	541.67	3,628
2009	677.51	219.98	166.67	1,041.67	3,481
2010	778.88	309.95	208.33	1,416.67	4,189
2011	1,021.58	375.63	250.00	1,625.00	5,069
2012	1,297.36	465.38	333.33	2,125.00	6,218
2008-2012	810.05	470.64	83.33	2,125.00	4,450 (mean)

Table 1 shows the average, minimum and maximum wind forecast and solar production over the years. Production is measured in MWh and installed capacity, in MW. For both technologies, the difference between minimum and maximum production, as well as the mean production substantially fluctuates over time.

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[6] Calculated as the sum of photovoltaic and thermal solar production.

This emphasizes the intermittent and unreliable character of those technologies.

Rainfall (measured in mm per m^2) and temperature are used as weather control variables (WeatherOnline, 2013). Solar and temperature are naturally higher correlated ($\rho = 0.49$) than solar and rain (*precipitation*), which are only weakly correlated ($\rho = -0.08$). The inclusion of temperature captures the effect of weather: higher temperatures are highly correlated with sunshine, but they may also affect conventional power plants. Run-of-the-River Hydro plants e.g. depend on the water level in the river; also other conventional plants use rivers for cooling. Not controlling for temperature would make the effect of solar generation biased, e.g. overestimating the effect of *solar* on *hydro.* The industry production index (OECD 2013) serves as Spain's economic performance indicator.

Table 2 gives an overview on the descriptive statistics of each variable used in our analysis.

Table 2: Descriptive Statistics of Data

Time Series	Variable Name	Obs	Mean	Std. Dev.	Min	Max	Source
Prices							
Power	Price	1827	47.12134	12.91916	2.466667	82.13042	OMIE(2013)
Oil	brent	1827	92.19025	24.57975	33.73	143.95	IEA(2013)
Gas	ttf_price	1827	20.42837	5.802648	7.2	40.1565	APX(2013)
Uranium	uxc_price	1827	52.51631	9.651544	40	90	UXC(2013)
Emission	eua_wprice	1827	9.446716	5.623614	0.015	16.865	EEX(2013)
Coal	coal_index	1827	104.4412	32.44161	56	224.75	PLATTS(2011),Argus(2013)
Quantity Sold at Power Exchange							
Hydro	q_hydro	1827	1588.825	901.0896	270.7	6472.296	OMIE(2013)
Pump	q_pump	1827	441.9877	287.1578	0	1407.283	OMIE(2013)
Nuclear	q_nuclear	1827	1593.403	653.9276	304.0917	5820.079	OMIE(2013)
Coal	q_coal	1827	1414.727	1079.746	0	5642.158	OMIE(2013)
CCGT	q_cc	1827	4778.429	2935.616	115.125	13200.96	OMIE(2013)
Fuel/Gas	q_fuel_gas	1827	528.4486	117.6727	205.5125	759.4125	OMIE(2013)
Demand							
Demand Power Exchange	q_demand	1827	22237.38	3337.577	13326.87	33503.61	OMIE(2013)
Special Regime Quantities							
Total Special Regime	specreg_actual	1827	9909.278	2818.552	4458.333	20166.67	REE(2013)
Power Exchange Special Regime	q_re_mercado	1827	10000.77	2656.686	4312.063	19861.38	OMIE(2013)
Wind Forecast	windforecast	1827	4538.593	2490.38	551.1765	13693.33	REE(2013)
Solar PV Total	solarpv_actual	1827	671.5015	316.9182	83.33334	1291.667	REE(2013)
Solar Thermal Total	solarthermal_actual	1827	138.5468	188.4821	0	833.3333	REE(2013)
Installed Capacities							
Hydro	hidro_inst	1827	14852.63	81.25765	14808	15014.72	REE(2009, 2013)
Pump	bombeo_inst	1827	2746.928	.1442007	2746.64	2747	REE(2009, 2013)
Nuclear	nuclear_inst	1827	7767.809	50.63277	7716	7852.98	REE(2009, 2013)
Coal	carbon_inst	1827	11408.85	152.5875	11247.61	11700	REE(2009, 2013)
Fuel/Gas	fuelgas_inst	1827	2272.678	1420.547	178.16	4401	REE(2009, 2013)
CCGT	cc_inst	1827	24106.2	1485.152	21677	25290.58	REE(2009, 2013)
Special Regime	especial_tot_inst	1827	33938.77	3541.956	28618	38884.52	REE(2009, 2013)
SR Wind	wind_spec_inst	1827	19582.89	2200.578	15977	22430.64	REE(2009, 2013)
SR Solar PV	solar_pv_spec_inst	1827	3685.364	422.1233	3207	4267.526	REE(2009, 2013)
SR Solar Thermal	solar_term_spec_inst	1827	764.902	681.7313	61	1949.97	REE(2009, 2013)
Other							
Precipitation	precipitation	1827	0.6109329	1.216827	0	15.875	Weatheronline(2013)
Temperature	temp	1827	18.70234	5.997503	5.334043	31.45833	Weatheronline(2013)
Industry Production	ind_prod	1827	84.97141	7.67428	75.28896	107.1877	NISS(2013)

5 Empirical Strategy

To estimate the effect of renewable generation on the wholesale price and the quantities produced by conventional power plants, the merit-order is used as the underlying structure. We endogenize each technology's produced quantity according to their rank in the merit order and the day-ahead price, in a structural VAR model. The quantity produced by each technology depends on the price and all the quantities produced by technologies to its left in the merit order. Production from renewable energies is treated as exogenous to the system. This reflects the current situation in Spain, with out-of-market support scheme for renewables. We also include demand, installed capacities, input costs for the different technologies, temperature and rainfall to control other exogenous influences not attributable to the effect of renewables. To capture seasonality and cyclic components, we include dummies for the days of the week (six), months (eleven) and years (four).

The six production technologies, in ascending order, based on their marginal costs, are: *hydro*, *nuclear*, *coal*, *CCGT*, *fuel/gas* and *pump* storage. *Hydro* and *nuclear* are baseload plants; *coal* and *CCGT* constitute the mid-merit order; and *fuel/gas* and *pump* storage are the peak plants. The ranking is based on information regarding the costs of power plants for the merit order from OECD (2010). The order is clear for most of the power plants. Fuel-switches mostly occur for coal and gas-fired plants as shown by Sunderkötter and Weber (2011), so we incorporate the change between the two technologies as a robustness check and change the order of *coal* and *CCGT* in an additional estimation.

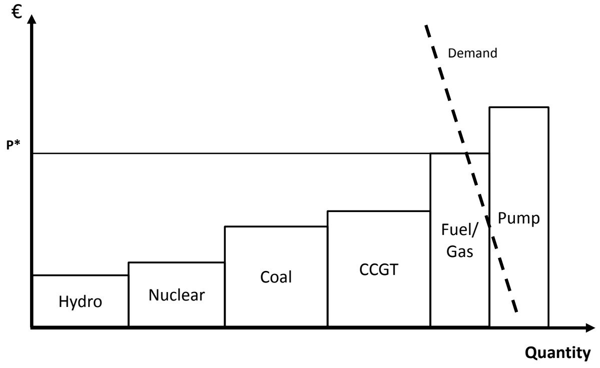

Figure 4: Merit Order

Vector Y comprises the endogenous variables. X is the vector of demand-specific shocks as well as fuel-type specific input factors. The vector RES describes the quantity produced under the *Special Regime*:

$Y = (price,\, q_{hydro},\, q_{nuclear},\, q_{coal},\, q_{ccgt},\, q_{fuelgas},\, q_{pump})$

$X = (Demand,\, Season,\, Installed\ Capacities,\, InputPrices)$

$RES = (SpecialRegime)$

The unrestricted VAR model therefore can be formalized as:

$$Y = A + BL(Y) + \Gamma RES + \Phi X + \epsilon \tag{1}$$

Figure 4 shows the underlying structure of the VAR model. The power plant with the highest marginal costs, which is still needed to cover demand, sets the price. All power plants to its left produce and earn money according to their marginal costs.

$$\begin{aligned} LnP_t \quad &= \quad cons_{pr} + \textstyle\sum_{i=1}^{k} \beta_{pr,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{pr,2,i} Hydro_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{pr,3,i} Nuclear_{t-i} + \sum_{i=1}^{k} \beta_{pr,4,i} Coal_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{pr,5,i} CCGT_{t-i} + \sum_{i=1}^{k} \beta_{pr,6,i} Fuel/Gas_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{pr,7,i} Pump_{t-i} + \Gamma_{pr} RES_t + \Phi_{pr} X_t + \epsilon_{pr,t} \end{aligned} \tag{2}$$

$$Hydro_t \quad = \quad cons_h + \textstyle\sum_{i=1}^{k} \beta_{h,1,i} LnP_{t-i} + \Gamma_h RES_t + \Phi_h X_t + \epsilon_{h,t} \tag{3}$$

$$\begin{aligned} Nuclear_t \quad &= \quad cons_n + \textstyle\sum_{i=1}^{k} \beta_{n,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{n,2,i} Hydro_{t-i} \\ &+ \quad \Gamma_n RES_t + \Phi_n X_t + \epsilon_{n,t} \end{aligned} \tag{4}$$

$$\begin{aligned} Coal_t \quad &= \quad cons_c + \textstyle\sum_{i=1}^{k} \beta_{c,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{c,2,i} Hydro_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{c,3,i} Nuclear_{t-i} + \Gamma_c RES_t + \Phi_c X_t + \epsilon_{c,t} \end{aligned} \tag{5}$$

$$\begin{aligned} CCGT_t \quad &= \quad cons_{cc} + \textstyle\sum_{i=1}^{k} \beta_{cc,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{cc,2,i} Hydro_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{cc,3,i} Nuclear_{t-i} + \sum_{i=1}^{k} \beta_{cc,4,i} Coal_{t-i} \\ &+ \quad \Gamma_{cc} RES_t + \Phi_{cc} X_t + \epsilon_{cc,t} \end{aligned} \tag{6}$$

$$\begin{aligned} Fuel/Gas_t \quad &= \quad cons_f + \textstyle\sum_{i=1}^{k} \beta_{cc,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{f,2,i} Hydro_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{f,3,i} Nuclear_{t-i} + \sum_{i=1}^{k} \beta_{f,4,i} Coal_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{f,5,i} CCGT_{t-i} + \Gamma_f RES_t + \Phi_f X_t + \epsilon_{f,t} \end{aligned} \tag{7}$$

$$\begin{aligned} Pump_t \quad &= \quad cons_p + \textstyle\sum_{i=1}^{k} \beta_{pu,1,i} LnP_{t-i} + \sum_{i=1}^{k} \beta_{pu,2,i} Hydro_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{pu,3,i} Nuclear_{t-i} + \sum_{i=1}^{k} \beta_{pu,4,i} Coal_{t-i} \\ &+ \quad \textstyle\sum_{i=1}^{k} \beta_{pu,5,i} CCGT_{t-i} + \sum_{i=1}^{k} \beta_{pu,6,i} Fuel/Gas_{t-i} \\ &+ \quad \Gamma_{pu} RES_t + \Phi_{pu} X_t + \epsilon_{pu,t} \end{aligned} \tag{8}$$

This structure (Figure 4) translates into equations 2 to 8. Estimating the price equation, all technologies are relevant. The equation for each technology, however, only considers technologies on its left in the merit order. The coefficients of power plants, to its right in the merit order, are constrained to zero. For instance, the production decision of a nuclear plant is not directly affected by that of a coal-fired plant as it has higher variable production costs. The opposite is true for the coal plant. If the cheaper technologies are already covering the whole demand, then the coal plant will not be dispatched. To control for temporary shifts within the merit order, we include the input prices for all power plant types and the price for emission certificates.

The inclusion of the production of the aggregated *Special Regime* does not uniquely identify the effect of intermittent technologies. It also comprises of small conventional power plants and renewables which can produce comparatively reliable, like waste or biomass. To split the *Special Regime* into its components, we use the wind forecast instead of the actual production as for the bidding behavior of the conventional plants only the forecast, and not the actual production, is relevant (Jonsson et al., 2010). The same is true for *solar*, but since forecasts are not publicly available, we use the daily averaged actual solar production provided by the market operator.

$$q_{special\_regime} = q_{solar} + q_{wind} + q_{other_{SR}} \tag{9}$$

The short-run merit order effect is based on the guaranteed feed-in of renewables and their lower marginal costs. The higher volatility of the residual demand, which has to be covered by the conventional power plant fleet, is, in contrast, due to the dependence of wind and solar power on weather. To show the effect of the intermittent renewables, we use both the entirety of the *Special Regime* (Model I) and its components (Model II).

Power generation by conventional power plants is constrained by the installed capacity of the different technologies. Installed capacity is only available on a yearly basis and is included as exogenous variables. Since power plant construction is tedious and installed capacities do not fluctuate heavily, this might not be very restrictive.

Demand is assumed to be exogenous to the VAR system. This is common practice in power markets (e.g. Gelabert et al., 2011). Demand may not be entirely price inelastic, but not all customers are exposed to real time wholesale prices; and even those who are, can be quite inflexible. Households have habitual patterns of consumption and are not subject to real-time pricing[7] since they have fixed contracts with their energy suppliers. The tourism industry, an important sector in Spain, is also quite inflexible in terms of electricity consumption. Energy intensive producers, like a steel mill (wherein the cost of production is highly dependent on electricity price) may be able to react more flexibly to price changes. An interruption of production during peak-price times, however, may be more costly than continuous production. Stopping production will only be profitable for very high price changes. In our dataset, the average price change,

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[7] Weighted by industry branches, the energy industry contributes 13.04% to the Spanish industry production; intermediate and capital goods impact the index by 37.7% and 20.64%, respectively. The rest constitutes non-durable and other consumer goods, 24.21% and 4.41% (NISS, 2013).

compared to the preceding hour, is 3.20€/MWh with a standard deviation of 3.93, 50% of the price changes are smaller 1.98€/MWh and 99% of the price changes are smaller than 18.21€/MWh. The reaction to those price changes can therefore be assumed as rather small.

We also test for exogeneity of demand in the price equation using the Davidson and MacKinnon (1989) test.[8] The null hypothesis of exogeneity is not rejected. The test is based on an instrumental variable approach and is described in appendix 8.

Table 3: Exogeneity Test for Demand

Davidson&MacKinnon	Coef.	Std. Err.	t
Demand	.0000257	.0001469	0.17

Solar data is only available on a daily basis. Aggregating the production data to the daily level underestimates the effect of solar, as solar production depends on sunshine, which only occurs between sunrise and sunset. In a second estimation, we therefore only take into consideration the hours between dawn and dusk.[9]

Before estimating the model, all the included time series are tested for the existence of unit roots. We use the augmented Dickey-Fuller (Dickey and Fuller, 1979) and Phillips-Perron (Phillips and Perron, 1988) test (see appendix Table 8) and find that the price time series, the input prices (except for the price for uran) and the industry-production index are I(1) variables, thus we take the first differences of those variables, which are all found to be I(0). For the price time series we take the logarithm LnPrice which is also found to be I(0). For all other time series, the null hypothesis that the variable follows a unit-root process can be rejected. We used the results of Schwarz's Bayesian information (SBIC) and Hannan and Quinn Information Criterion (HQIC) for the lag order selection.[10]

We also used the Hannan-Quinn and the Schwarz-Bayes information criteria for the lag length selection of the whole VAR model. Eight and three lags, respectively, are found for the simultaneous lag length selection by the information criteria. From an economic point of view, a short lag length is preferable. As the dynamics over the year and during the week are captured by the seasonality dummy and we also aggregated the data to the daily level, only the previous days should have an immediate impact. Thus, for the reported results, the SBIC

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[8] The test is repeated for different specifications, the test results remain qualitatively unchanged in all settings.

[9] Sunrise and sunset time is for Madrid (TheWeatherChannel.com, 2013).

[10] We also tested for cointegration of the endogenous variables. As only the price series is integrated of order one and all other time series (except the input prices) are I(0) the economic interpretation of the cointegration test is misleading. The fact that there exists one or several linear combination of the variables that is I(0) does not necessarily mean that they follow a common equilibrium path, when several of the time series are already I(0). Furthermore, we also take the logarithm of price which is found to be I(0).

lag length is chosen; the result remains qualitatively unchanged for the higher lag order and is available upon request.

After estimating the restricted VAR model, we used the Lagrange-multiplier test (Johansen, 1995) to test for autocorrelation. We found some persistent autocorrelation in the residuals Newey and West (1987) standard errors are used to allow for autocorrelation up to a certain lag length. As proposed in Newey and West, (1987) the lag length for the correction is chosen as the integer of $4(T/100)^{\frac{1}{4}}$ whereas T is the number of observations in the dataset. Results are robust to higher number of lags.

6 Results

We are interested in the effect the exogenous variables *Special Regime* and *wind*, *solar* and *other RES* on the endogenous merit order. Table 4 reports the results for those variables in each of the seven equations. The first two columns show the estimated equation and the dependent variable in this equation. The other columns show the price or quantity impact of a 1-MWh increase of either *Special Regime*, *wind*, *solar* or *other RES* the respective equation. In model I the results for the whole *Special Regime* are reported. Model II shows the influence of the components of *wind*, *solar* and *other RES*.

Overall, the *Special Regime* decreases the price. A one MWh increase in *Special Regime* generation decreases the price by 0.003% - that's a decrease of 3% for an increase of one GWh. This effect is induced by *wind*. On the contrary, an increase in the production of *solar* and *other RES* increases the price.

The effect on the merit order is negative for all technologies but insignificant for *nuclear*. Again, *wind* is the driving force behind this result. An increase in *wind* energy production reduces the generated quantities of all technologies significantly - except for *nuclear* (model II). The results for *solar* and *other RES* are ambiguous.

Table 4: Impact of Special Regime and its Components

	Model I	Model II		
Eq./ Dep. Var.	Special Regime	Wind	Solar	Other RES
(2) LnPrice	-0.0000306***	-0.0000318***	0.0000545***	0.0000160*
(3) Hydro	-0.0223019***	-0.0291984***	-0.0094671	0.0898763***
(4) Nuclear	-0.0004307	0.0000257	-0.047776	-0.0018914
(5) Coal	-0.0933551***	-0.0974866***	0.1093186	-0.0696695*
(6) CCGT	-0.1982958***	-0.3461214***	-0.2825958**	-0.1358050**
(7) Fuel/Gas	-0.0013968**	-0.0016611**	-0.0015485	0.0044956*
(8) Pump	-0.0183483***	-0.0196749***	0.0013187	0.0201682**
N	1824	1824	1824	1824

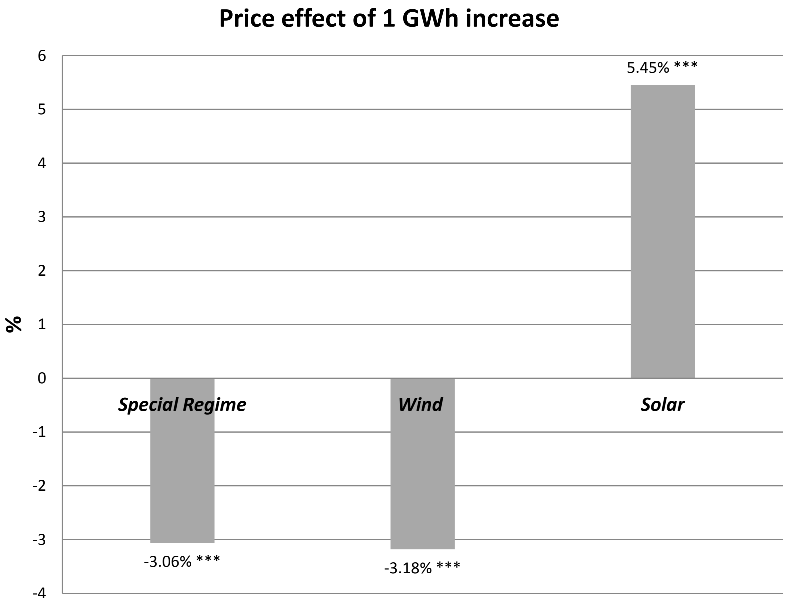
Level of Significance: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

An increase of 1-GWh in *solar* production increases the price by 5.45%, whereas only *ccgt* plants are significantly affected negativ in the merit order. Also, one GWh increase decreases CCGT plants' production by 282.60 MWh. The same is true for *other RES*: the price increases with an increased production. Production by mid-merit plants, such as *coal* and *ccgt*, decreases; but *hydro* and peakload plants (*fuel/gas* and particularly *pump*,) benefit from more power fed-in by *other RES*.

Note that the model controls for the influence of temperature and rain. Aside from the effect of renewables, weather conditions can also cause fluctuations in the generation of conventional plants. A long drought could, for example, lead to lower water levels in rivers. This forces power plants to reduce their production as cooling water becomes scarce.

The effect of *solar* is contrary to expectations. Renewable generation reduces the demand which has to be covered by conventional power plants. Additionally, *solar* can only produce when the sun shines - which is mainly during peak hours, thereby cutting off price peaks. Figure 5 shows the price effect of one GWh increase of single RES generation technologies.

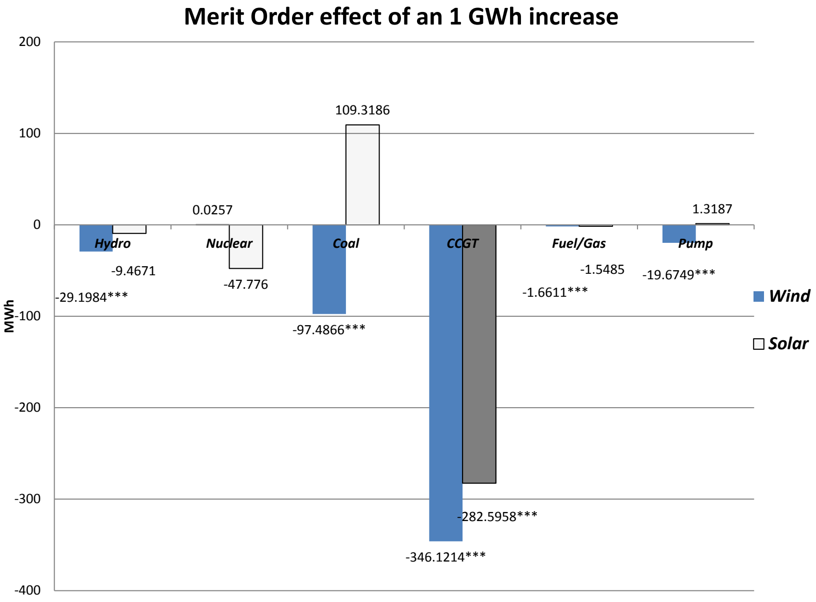
Figure 5: Price Effect of Renewables



The effect of *solar* is largest in magnitude and offsets the negative price effect of *wind*. An increase of 1 GWh, however, is relatively much larger and is more unlikely to happen for *solar* than for *wind*. The average production of *solar* over all years was 0.81 GWh, only in 2011 and 2012 did it reach an average production of over 1 GWh over the whole year (see Table 1). Thus, an increase of one GWh is equal to twice the current production. In the case of *wind*, an increase of 1 GWh constitutes only 22% of its average production in the specified five years, which is still a substantial but also a more likely increase.

Not all technologies are affected to the same extent. Figure 6 shows that in contrast to the prediction of the short-run merit order effect (e.g. de Miera et al. 2008), it is not the peak plants suffer the most, but the mid-merit plants. The prioritized feed-in of renewables effectively reduces the demand to be covered by conventional power plants. But baseload plants seem to be minimally affected if not totally unaffected; moreover, the flexible peak plants seem to reduce their quantities only to a small extent, which leaves mid-merit plants the ones absorbing the influence of renewable on the power market.

Figure 6: Merit Order Effect of Renewables



The positive price effect of *solar* cannot be explained by the effect on the merit order in Table 4. The production of *solar*, however, is only available on a daily basis. As we also aggregate the hourly production data and the price to the daily average, we underestimate the effect of solar power. *Solar* can only produce during daytime but the aggregated data on quantities produced and the price, also contains night hours when it is impossible to produce solar energy. Table **??** therefore shows the effect of *solar* during daylight hours.[11]

The effects for the whole *Special Regime* become more distinct during daytime, except for *fuel/gas* which is no longer significant; but *nuclear* now produces significantly less. The same is true for *wind*: the effect becomes stronger for most

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[11] We took the hours between sunrise and sunset for Madrid for each day to determine the hours of possible production by *solar*. Before we aggregated the data to the daily level using all 24 hours, now we only use the daylight hours to aggregate data to the daily level. Note that we have data on quantities produced within the merit order and windforecast on a hourly base.

Table 5: Impact of Special Regime between Sunrise and Sunset

	Model I	Model II		
Eq. Dep. Var.	Special Regime	Wind	Solar	Other RES
(2) LnPrice	-0.0000398***	-0.0000454***	0.0000749**	0.0000467***
(3) Hydro	-0.0852349***	-0.1027663***	-0.1064387	0.2087144***
(4) Nuclear	-0.0145175***	-0.0030491	-0.3305512***	-0.1640257***
(5) Coal	-0.1607183***	-0.1502956***	-0.1011762	-0.3522494***
(6) CCGT	-0.2419864***	-0.4194985***	-0.4965494***	-0.2241564***
(7) Fuel/Gas	0.001901	0.0005658	0.0116572	0.0224018***
(8) Pump	-0.0304683***	-0.0385795***	0.1444175***	0.0654165***
N	1824	1824	1824	1824

Level of Significance: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

technologies as well as for the *price*, but the influence on *fuel/gas* diminishes during daytime. The aggregation to daytime is not very meaningful for wind power, but roughly coincides with the peak hours in Spain.

Interestingly, *solar* now affects *nuclear* and *ccgt* negatively and statistically significant, and the production of *pump* increases, when the feed-in by *solar* increases. This means that the mid-merit order, and to a smaller degree baseload, reduce their production because of daytime solar power production, making more expensive and more flexible peak plants benefit from the effect of unsteady generation.

The same is true for *other RES*, where the peak plants produce more, and the other plants in the merit order, except for *hydro*, reduce their production when generation increases. *Other RES* has been quite stable and predictable in production.

The results remain qualitatively unchanged for fuel switches between coal and gas-fired power plants (Sunderkötter and Weber 2011) and for higher order of lags.[12]

7 Conclusion

This chapter analyzes the impact of power generation, based on renewable resources, on wholesale power prices and conventional power generation in Spain. The data set contains information on daily averages of actual production and quantities sold at the Spanish power exchange from 2008 to 2012.

We estimate a structural vector autoregressive model, using the merit order as the underlying structure. The empirical evidence suggests that the merit

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[12] Results are available upon request.

order effect is not as clear cut as theory predicts. The main driver of renewable resources is wind power, which exhibits the expected negative impact on prices and on the quantities produced by conventional plants. On the contrary, solar power has a positive effect on wholesale prices.

Given the merit order of production, mid-merit plants are affected more than peakload or baseload plants. As the share of renewable energy resources is not yet large enough, baseload plants may not be affected as of now. The residual demand is still sufficiently large for those plants to run for most of the hours during the year. Peakload plants, on the other hand, may easily adapt to the higher volatility of the residual demand, leaving mid-merit plants to suffer the most from increasing RES production. If these findings still hold for higher shares of RES in power generation, then mid-merit power plants could be potential candidates for a market exit.

The Spanish market design already includes capacity payments for the availability of generation capacity. These could become insufficient, if CCGT and coal-fired power plants' runtimes continue to decline. If CCGTs will be crowded out in the long run, adjustments to the market design may be necessary, but this would depend on ecological goals, preferences regarding the power price and security of supply.

To guarantee security of supply, conventional power plants have to cover demand whenever unusual or unexpected weather conditions reduce wind and solar production to a minimum level. Depending on the weather condition, certain power plants may have to operate on standby for long periods during the year or even longer. Inability to cover full demand in times when production by renewables unexpectedly drops can lead to blackouts in situations of scarcity. As much as power production by renewable resources is ecologically desirable, security of supply is as essential for the industry and society.

In general, sophisticated capacity mechanisms might be necessary to complement energy-only markets to guarantee security of supply or to prevent certain technologies from leaving the market. This, however, leads to high costs of introduction and requires a European-wide change of the market design. Furthermore, this will also have substantial influence on competition (Böckers et al. 2011). While some markets like PJM in the United States have decided to implement a full-blown capacity market, the UK has abandoned such a mechanism. This unclear development of the different market designs will increase uncertainty, but since investments in power plants are, by nature, long term, investors will need a stable environment with little changes in market design.

The current support schemes often promote investments in certain technologies, independent of any inefficiency caused in the generation mix. The ultimate ecological goal is to reduce carbon emission and make power production more sustainable, not the promotion of certain production technologies. If conventional power plants are priced out of the market, problems inherent to the energy-only market (such as the missing-money problem) may be emphasized. Changes in the market design - aimed to stimulate investment in conventional resources or to prevent those technologies from leaving the market - may be necessary. These market designs are typically more restrictive and they induce higher costs to consumers.

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8 Appendix

Test for exogeneity of Demand

Using demand and supply can cause a simultaneous causality problem if demand cannot be considered exogenous to the supply system. As actual demand is mostly unobservable, equilibrium prices and quantities are considered for estimation. In equilibrium supply and demand are equal and a regression of solely quantities on prices will not help to identify whether the supply or demand function has been estimated. To solve the identification problem demand- or supply-specific factors are included. Since we are interested in estimating the price supply function, we estimate the demanded quantity. Important factors for demand are the economic performance of a country, e.g. energy-intensive industry, seasonal and temperature effects (REE 2013b) as well as exogenous demand shifters like holidays. Therefore, we assume demand to be a function of the price, past demand, economic factors, etc.:

$$D = F(price,\ past\ demand,\ economic\ factors,\ weather,\ season,\ holiday). \tag{10}$$

We use industrial production as an economic performance indicator, and average daily temperature, rainfall, and dummy variables for seasons and public holidays. The simultaneity bias also depends on the elasticity of demand. If demand was entirely price inelastic, the problem would be negligible. We estimate demand using:

$$\begin{aligned} D &= cons + \sum \alpha_d D_{t-i} + \alpha_y Year_y + \alpha_m Month_m + \alpha_j Day_j + \alpha_5 Ind\_Prod \\ &+ \alpha_6 temp + \alpha_7 Precipitation + \alpha_8 Holiday + residual \end{aligned} \tag{11}$$

To test for exogeneity of demand we use the Davidson & MacKinnon (1989) test.[13] The null hypothesis of exogeneity is not rejected (see Table 7); and since exogeneity is not rejected, we include demand in our estimation.

Table 6: Exogeneity Test for Demand

Davidson&MacKinnon	Coef.	Std. Err.	t
Demand	.0000257	.0001469	0.17

Table 7: Exogeneity Test for Demand

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[13] The test is repeated for different specifications the test results remain basically unchanged.

Table 8: Results for Unit Root Tests - Daily

	Dickey-Fuller (SBIC)		Dickey-Fuller (HQIC)		Phillips-Perron (SBIC)		Phillips-Perron (HQIC)	
Variable	constant	trend	constant	trend	constant	trend	constant	trend
price	-3.359**	-3.413**	-2.892**	-2.939	-6.923***	-7.182***	-7.240***	-7.530***
lnprice	-5.814***	-5.870***	-4.674***	-4.719***	-9.886***	-10.006***	-10.224***	-10.359***
q_demand	-4.903***	-6.604***	-4.098***	-5.429***	-12.992***	-17.496***	-14.878***	-19.832***
solar	-2.871**	-3.706**	-2.384	-2.810	-4.901***	-7.931***	-4.936***	-8.352***
windforecast	-15.721***	-16.578***	-13.861***	-14.688***	-19.373***	-20.186***	-19.039***	-19.849***
q_other_REE	-3.963***	-4.962***	-3.963***	-4.962***	-23.915***	-27.865***	-23.915***	-27.865***
sr_total	-14.076***	-14.235***	-14.076***	-14.235***	-18.478***	-18.620***	-18.478***	-18.620***
q_hydro	-4.456***	-4.746***	-3.564***	-3.876**	-6.191***	-6.543***	-6.996***	-7.411***
q_pump	-5.152***	-7.884***	-5.152***	-7.884***	-19.401***	-25.858***	-19.401***	-25.858***
q_nuclear	-5.940***	-6.420***	-4.805***	-5.233***	-12.369***	-13.484***	-13.659***	-14.955***
q_coal	-5.232***	-5.240***	-5.097***	-5.116***	-13.892***	-14.244***	-15.912***	-16.325***
q_cc	-3.209**	-6.204***	-2.816*	-5.259***	-12.829***	-21.014 ***	-14.579***	-22.798***
q_fuelgas	-7.811***	-7.811***	-7.811***	-7.811***	-9.572***	-9.570***	-9.572***	-9.570***
brent	-1.299	-1.739	-1.299	-1.739	-1.283	-1.679	-1.283	-1.679
ttf_price	-2.683*	-2.895	-2.420	-2.664	-2.716*	-2.927	-2.571*	-2.784
uxc_price	-3.950***	-3.717**	-3.950***	-3.717**	-3.937***	-3.538**	-3.937***	-3.538**
eua_wprice	-1.840	-1.428	-1.840	-1.428	-1.819	-1.393	-1.819	-1.393
coal_index	-1.629	-1.624	-1.558	-1.550	-1.380	-1.390	-1.401	-1.412
d.brent	-42.031***	-42.027***	-42.031***	-42.027***	-42.031***	-42.027***	-42.031***	-42.027***
d.uxc_price	-10.626***	-10.711***	-10.626***	-10.711***	-42.803***	-42.867***	-42.803***	-42.867***
d.ttf_price	-26.921***	-26.922***	-26.921***	-26.922***	-43.701***	-43.694***	-43.701***	-43.694***
d.eua_wprice	-40.884***	-40.918***	-40.884***	-40.918***	-40.884***	-40.918***	-40.884***	-40.918***
precipitation	-18.188***	-19.004***	-4.120***	-4.449***	-21.449***	-22.324***	-29.968***	-30.019***
temperature	-4.023***	-3.991***	-4.023***	-3.991***	-4.649***	-4.623***	-4.649***	-4.623***
ind_prod	-1.128	-1.109	-1.128	-1.109	-1.126	-1.112	-1.126	-1.112
d.ind_prod	-30.222***	-30.224***	-30.222***	-30.224***	-42.714***	-42.713***	-42.714***	-42.713***

Null hypothesis: variable contains a unit root - level of Significance: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Table 9: Results for Unit Root Tests - Daylight

	Dickey-Fuller (SBIC)		Dickey-Fuller (HQIC)		Phillips-Perron (SBIC)		Phillips-Perron (HQIC)	
Variable	constant	trend	constant	trend	constant	trend	constant	trend
price	-14.001***	-13.998***	-11.753***	-11.749***	-45.543***	-45.538***	-45.851***	-45.859***
lnprice	-43.038***	-43.063***	-13.588***	-13.607***	-43.038***	-43.063***	-43.038***	-43.062***
q_demand	-7.995***	-9.299***	-8.098***	-9.470***	-37.050***	-37.879***	-37.073***	-37.959***
solar	-16.329***	-16.324***	-12.265***	-12.323***	-40.487***	-40.481***	-37.195***	-37.187***
windforecast	-39.444***	-39.494***	-39.444***	-39.494***	-39.444***	-39.494***	-39.444***	-39.494***
q_other_REE	-35.705***	-35.715***	-11.859***	-11.897***	-35.705***	-35.715***	-38.455***	-38.439***
sr_total	-40.358***	-40.426***	-28.646***	-28.726***	-40.358***	-40.426***	-40.354***	-40.423***
q_hydro	-13.444***	-13.729***	-10.192***	-10.798***	-33.998***	-33.986***	-35.489***	-35.643***
q_pump	-34.157***	-34.172***	-34.157***	-34.172***	-39.752***	-39.752***	-39.752***	-39.752***
q_nuclear	-9.912***	-10.215***	-8.541***	-9.231***	-45.748***	-46.371***	-47.044***	-48.737***
q_coal	-13.519***	-13.531***	-7.692***	-7.742***	-39.002***	-39.008***	-38.855***	-38.859***
q_cc	-12.132***	-12.215***	-9.526***	-9.851***	-38.139***	-38.169***	-40.213***	-40.556***
q_fuelgas	-11.397***	-11.497***	-9.819***	-11.355***	-35.389***	-35.410***	-34.753***	-35.730***
brent	-1.299	-1.739	-1.299	-1.739	-1.283	-1.679	-1.283	-1.679
ttf_price	-2.683*	-2.895	-2.420	-2.664	-2.716*	-2.927	-2.571*	-2.784
uxc_price	-3.950***	-3.717**	-3.950***	-3.717**	-3.937***	-3.538**	-3.937***	-3.538**
eua_wprice	-1.840	-1.428	-1.840	-1.428	-1.819	-1.393	-1.819	-1.393
coal_index	-1.629	-1.624	-1.558	-1.550	-1.380	-1.390	-1.401	-1.412
d.brent	-42.031***	-42.027***	-42.031***	-42.027***	-42.031***	-42.027***	-42.031***	-42.027***
d.uxc_price	-10.626***	-10.711***	-10.626***	-10.711***	-42.803***	-42.867***	-42.803***	-42.867***
d.ttf_price	-26.921***	-26.922***	-26.921***	-26.922***	-43.701***	-43.694***	-43.701***	-43.694***
d.eua_wprice	-40.884***	-40.918***	-40.884***	-40.918***	-40.884***	-40.918***	-40.884***	-40.918***
precipitation	-18.188***	-19.004***	-4.120***	-4.449***	-21.449***	-22.324***	-29.968***	-30.019***
temperature	-4.023***	-3.991***	-4.023***	-3.991***	-4.649***	-4.623***	-4.649***	-4.623***
ind_prod	-1.128	-1.109	-1.128	-1.109	-1.126	-1.112	-1.126	-1.112
d.ind_prod	-30.222***	-30.224***	-30.222***	-30.224***	-42.714***	-42.713***	-42.714***	-42.713***

Null hypothesis: variable contains a unit root - level of Significance: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

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