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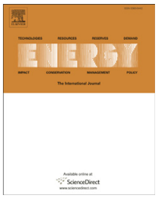

Evaluation of a cross-border electricity interconnection: The case of Spain-France

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ABSTRACT

This paper focuses on the economics of a cross-border transmission interconnector. The domestic spot electricity price is modelled as a stochastic process with mean reversion and jumps; it also includes a deterministic part that accounts for hourly and daily sasonalities along with non-working days. The two domestic spot prices are assumed to be correlated. As an illustration of the approach, we consider the particular case of the interconnector between Spain (an 'electric island') and France. Domestic prices are first calibrated and then used for simulating the stochastic behavior of the price gap between the two countries. In addition, the actual import/export behavior as a function of the price gap is captured by a Tobit model fitted from observed data. This model is then combined with the simulated price gaps to compute a multiple series of hourly prices and exports/imports of electricity through the interconnector. Drawing on these simulations we derive the probability distributions of revenues and expenses from exports and imports, and also some risk measures. According to our results, the economics of this interconector depends on different domestic seasonalities (hourly and daily), the growing trend of the price gap and some stochastic idiosyncrasies. They call for an expanded link.

1. Introduction

Cross-border power interconnections bring about a number of benefits for participating countries and beyond [1], among them: (*i*) enhance security of electricity supply (SoS) by providing support functions between interconnected electrical systems; (*ii*) ensure the stability and frequency of the two systems; (*iii*) exploit price differences through power imports and exports thus increasing economic efficiency; (*iv*) harness renewable energy sources by allowing the transmission of excess renewable generation; (*v*) develop the Internal Energy Market in Europe.[1]

This paper falls within the literature about power transmission expansion with a special focus on interconnector economics, i.e. item (*iii*). A number of models have been proposed to address power trade based on price differentials.[2] Many of them are applied to European countries (whether looking backward or forward in time), be it under general or partial equilibrium conditions. Typically, they are optimization models that aim to maximize social welfare or minimize system costs, for instance. They usually consider a single year (or fractions of it) with daily/hourly time steps. Importantly, they tend to be deterministic; the authors account for risks and uncertainties by simulating the models under several scenarios (e.g. without and with a particular expansion of the transmission grid). Besides, the optimization process results in a series of (daily/hourly) power prices, yet their properties are not shown. Thus, whether those optimization-based prices display the usual characteristics in actual power markets is all but impossible

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[1] There can well be conflicts among these goals; see for instance Ref. [32].

[2] Full price convergence is not an objective as such: it would entail over-investing in network infrastructures [33].

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for outsiders to tell.

Our paper introduces a novel approach that puts electricity prices at the forefront of the analysis. It looks at actual wholesale prices in two specific countries (domestic markets) with a common interconnector. The paper proposes a stochastic model where (correlated) domestic spot prices display seasonality, mean reversion and jumps. The aim here is to evaluate a particular cross-border interconnector from the viewpoint of revenues. Consequently, we also consider actual flows of electricity in both directions. Drawing on the latest price and quantity data publicly available we simulate the revenues to the interconnector in the near future. Hence we not only provide average estimates but probability distributions (i.e. risk profiles) as well. We further illustrate our approach by applying it to a singular case study; this is the second contribution of our paper.

Right now, Spain is akin to an “electric island” because of its low interconnection ratio of 2.8% in 2019 (computed as the sum of the import capacities divided by the installed generation capacity). This low rate is very far from the EU goal of 10% for 2020 and the minimum of 15% for 2030; ENTSO-e [2]. The Spanish electricity system is connected with France, Portugal, Morocco and, to a lesser extent, Andorra. Anyway, the short AC interconnection with France is very important because it gives access to the vast European electricity market.[3] The French interconnector has a commercial exchange capacity of 2800 MW.[4] After the commissioning of a new project (crossing the Bay of Biscay) this capacity will increase up to 5000 MW; its commercial use is planned to start in 2024 or 2025 [3]. This way the interconnection ratio will rise to about 5%. Thus, Spain will remain an “electric island” for decades to come. This condition leaves it especially vulnerable to low-frequency, high-impact events, whether of natural, accidental or malicious origins.

According to our results, Spanish exports would amount to €27 million on average over the three-year period 2020–22, while imports from France would entail average expenses of €964 million. These figures allow justify substantial new investment (taking [4]; and [5]; as benchmarks).[5] One of the drivers behind this result is the stronger upward trend of Spanish power price. As expected, when we impose the restriction of no growth in domestic prices the balance for Spain improves.

The paper continues as follows. Section 2 reviews the literature on the potential gains from enhanced cross-border interconnectors, preferably (though not exclusively) with a focus on the EU. Then Section 3 introduces the theoretical framework, starting from the stochastic model for domestic power price. Section 4 focuses on the two countries involved in this paper; it provides background data about domestic spot prices (at the hourly and daily time scales) along with power exports and imports. The price model is calibrated n Section 5. Next in Section 6 we draw on the earlier parameter estimates to simulate the price in each country (and the ensuing price gap) over the period 2020–2022. On the other hand, Section 7 estimates a model of power flows between France and Spain. Cross-border flows and simulated prices allow simulate the transmission income to the interconnector in Section 8. A sensitivity analysis with respect to the growth rate of power prices is undertaken in Section 9. Section 10 concludes.

2. Literature survey

First, we proceed from a ‘macro’ to a ‘micro’ perspective: EU nations, regions, and industry stakeholders (producers, consumers, and transmission system operators). Then we consider some reasons behind inefficient arbitrage transmission (i.e. flows in the ‘wrong’ economic direction) in pairs of neighbouring markets.

Abrell and Rausch [6] find considerable scope for two-way cross-border trade in Europe (e.g. between Spain and France).-Power price differentials are far from unidirectional. Further, very frequently there are sizeable price gaps between countries with a cross-border interconnection (e.g. France and Spain). The gaps can certainly arise when transmission constraints are binding. And also when they are not because of: (i) transmission losses and/or ramping restrictions [7]; (ii) inability of the interconnector's owner to take simultaneous long (i.e. purchasing) and short (i.e. selling) positions in the two locations (because market liquidity in at least one of them is too thin; [8].

Göransson et al. [9] analyse the European power system at the NUTS-2 level, which results in 50 regions. Their results for 2020 show an annual average marginal cost around 50 €/MWh in the Spanish region ES2 and close to 30 €/MWh in the French one FR2. This ‘congestion’ gap implies that the ‘marginal connection capacity value’ over 8760 h amounts to some 173 Mill € per year (rendering this connection one of the five AC interconnections with the highest values). Further, these two regions are a case in so-called ‘all-hour congestion’.

Spiecker et al. [10] find utilization rates of the line connecting France and Spain around 90% both with and without grid extension in 2020 (about 2/3 of that rate corresponds to power flowing from France to Spain, and 1/3 to reverse flow). These high rates suggest that bottlenecks occur frequently. Under the expanded grid the average of absolute price differences between these two countries is cut in half.[6] The share of variable wind infeed is significantly higher in Spain than in France, which leads to more frequent reversals in the flow direction. Overall, France is one of the major beneficiaries of new interconnectors; they have a positive impact on producer surplus but a negative one on consumer surplus and congestion rent. Pudjianto et al. [11] consider the period 2010 to 2050. They find that reinforcing the interconnection allows Spanish consumers to access competitive offers from foreign producers, which leads to lower power prices and producer surplus. Yet not all producers suffer; for example, solar PV producers gain while wind producers lose.[7] Instead, French producers will meet a higher demand, which results in an increase of power prices in France (to the detriment of French consumers).

At this point, it is worth noting that electricity does not always flow as price arbitrage would suggest.[8] Clements et al. [12] find instances of electricity flowing from Queensland to neighbouring New South Wales despite the former having a higher price. They show that these instances are due to nodal transmission constraints in Queensland only (not to constraints across regional boundaries). On the other hand, Bunn and Zachmann [13] show analytically that a dominant generator in one location, under special circumstances, may choose to export power (to a more competitive neighbouring market) against the direction of efficient arbitrage. Further, as those

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[3] The interconnector project was first proposed in 1980 (followed by a second proposal in 2003); it started operation 35 years later [34].

[4] The net transfer capacity (NTC) typically sets the commercial (rather than the physical) capacity between two countries.

[5] The potential value of an interconnector is much higher. In addition to these revenues from day-ahead coupling it comprises the benefits from intraday coupling, shared balancing resources, avoided undesirable unscheduled flows, and reduced curtailment. According to Ref. [5]; revenues from day-ahead arbitrage make up around 25% of total value.

[6] The average of those differences between two regions over a year indicates the welfare effect of a *marginal* line investment.

[7] This can be related to the different levelized cost of electricity (LCOE) of these technologies; Abadie and [35].

[8] Under some circumstances, a flow in the ‘wrong economic direction’ may be socially beneficial if its welfare economic cost is smaller than the welfare economic benefit of the congestion relieved by such a flow; [33].

special circumstances do apply in the case of the Anglo-French Interconnector, they provide evidence that such flow reversions do occur in reality.

The above papers focus on pairs of neighbouring countries for the most part, and we follow suit. Nonetheless, this is a partial perspective. In an AC network, physical electricity flows are hard to control and cannot be directed. Therefore, in highly meshed transmission networks (e.g. continental Europe) the directly-connected countries are not the only players in determining cross-border flows. Changes in spatial generation/load patterns in non-neighbouring countries reverberate beyond national borders and impact other regions and/or cross-border interconnections in the network. We do not consider these effects beyond immediate neighbours[9]; ignoring general equilibrium/network effects is not so much of a problem when addressing links to isolated systems like Spain [14]. Further, this is not only a technical issue. As Kunz [15] points out, the identification of flow patterns has important effects on the available cross-border capacity and hence on electricity spot markets. We leave this issue aside.

3. Theoretical framework

Our ultimate goal is to simulate the transmission income to the interconnector in the near future (the three-year period 2020–2022). We first introduce a stochastic model of power prices. This model is then to be estimated with publicly available data. Parameter estimates allow simulate power prices in the two countries. Next, it is necessary to estimate a model of power transmission along the interconnector. However, cross-border flows are subject to some constraints; this leads to 'censoring' several observations, which in turn calls for abandoning the linear regression model and replacing it with a so-called Tobit model. Upon its estimation (with STATA), it is finally possible to simulate power prices along with flows and derive simulated revenues (with MATLAB).

3.1. *A stochastic model of electricity prices*

As Weron [16] points out, the European convention is to refer to the day-ahead electricity price as the 'spot price'. We use spot prices because of their greater informational content and liquidity. Besides, they reflect *market fundamentals* (as opposed to *expectations* about future market fundamentals, which are reflected in the prices of futures and forward contracts on electricity); Hirth [17].

Several approaches have been developed for analyzing and predicting electricity prices; see Weron [16]. So-called reduced-form (quantitative, stochastic) models characterize the statistical properties of power prices over time. We refer in particular to Escribano et al. [18]; Lucía and Schwartz [19]; Seifert and Uhrig-Homburg [20]; and Villaplana [21]. We use a modified version of the stochastic model in MathWorks [22] to account for the effects of non-working days. Specifically, we describe the (natural logarithm of) daily spot price p_t in a given country $i = \{\mathrm{S\ (Spain),\ F\ (France)}\}$, under the statistical measure, as the sum of two components:

$$\ln\left(p_t^i\right) = f^i(t) + X_t^i \tag{1}$$

The first part, $f^i(t)$, is deterministic. It includes annual and semi-annual seasonalities (through sine and cosine functions), a trend (t), and a dummy variable (D_t^i) for weekends and public holidays (we consider only official national holidays, not regional ones): $D_t^i = 1$ on weekends and non-working days, $D_t^i = 0$ otherwise. It also includes a constant (β_7^i) along with 24 parameters (β_j^i) that correspond to the hourly seasonality $(H_{j-7,t}, j = 8, \ldots 31)$ in each country:

$$\begin{aligned} f^i(t) = {} & \beta_1^i \sin(2\pi t) + \beta_2^i \cos(2\pi t) + \beta_3^i \sin(4\pi t) + \beta_4^i \cos(4\pi t) \\ & + \beta_5^i t + \beta_6^i D_t^i + \beta_7^i + \sum_{j=8}^{31} \beta_j^i H_{j-7,t} \end{aligned} \tag{2}$$

The second part, X_t^i, is modelled as a stochastic equation[10]

$$dX_t^S = \left(\alpha^S - \kappa^S X_t^S\right)dt + \sigma^S dW_t^S + J^S\left(\mu_j^S, \sigma_j^S\right)dq_j^S \tag{3}$$

$$dX_t^F = \left(\alpha^F - \kappa^F X_t^F\right)dt + \sigma^F dW_t^F + J^F\left(\mu_j^F, \sigma_j^F\right)dq_j^F \tag{4}$$

$$E\left(dW_t^S\, dW_t^F\right) = \rho dt \tag{5}$$

Specifically, Equations (3) and (4) are Ornstein-Uhlenbeck (OU) mean-reverting processes with jumps. They include three terms on the right hand; the first one is a function of X_t^i, while the other two are stochastic. Leaving the latter aside for a moment, the equation can be rewritten as $dX_t^i = (\alpha^i - \kappa^i X_t^i)dt = \kappa^i\left(\frac{\alpha^i}{\kappa^i} - X_t^i\right)dt$. Thus, the (log) stochastic part of the electricity price in country i tends toward α^i/κ^i in the long term, with a reversion speed κ^i. If X_t^i falls below its long-run quilibrium value the parenthesis will be positive, which induces an increase in its value $(dX_t^i > 0)$; and conversely: if X_t^i rises above α^i/κ^i the parenthesis will be negative, pushing X_t^i downwards $(dX_t^i < 0)$. In sum, when X_t^i departs from its long-term equilibrium (due to the impact of stochastic shocks, namely OU and jumps), the first term tends to restore the equilibrium (always subject to shocks). Besides, the higher the speed of reversion κ^i, the sooner X_t^i approaches its equlibrium value. Now, the second term generates a random behaviour without jumps. The volatility of the mean-reverting process is σ^i; dW_t^i is the increment to a standard Wiener process. The third term is a Poisson process with intensity λ^i (the mean rate of event occurrence); if time is measured in years then λ^i jumps are expected per year. The jump size is normally distributed with mean μ_j^i and volatility σ_j^i. Here dq_j^i is a Poisson process such that $dq_j^i = 1$ with probability $\lambda^i dt$, and $dq_j^i = 0$ with probability $1 - \lambda^i dt$. We assume that dW_t^i and dq_j^i are independent. Note that Equations (3) and (4) allow negative values (the logarithm of some low electricity prices can be negative).

On the other hand, sometimes both French and Spanish prices can move stochastically for common reasons. Equation (5) shows that these processes are correlated as measured by ρ. In this regard, the higher the price correlation, the lower the ability to benefit from the price gap between countries and hence from the interconnector.

3.2. *Calibration of the price model*

Calibrating the above jump-diffusion model is related to the

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[9] [36] adopt this broader view but aim at a different goal.

[10] This second part can be interpreted as a special case of the general stochastic differential equation for the increment of the (deseasonalized and detrended) spot electricity price in Ref. [16].

Table 1
Hourly prices and power flows: Descriptive statistics (2016–2019).

	Mean	Minimum	Maximum	Standard Deviation	Skewness	Excess Kurtosis	Percentile 5%	Percentile 95%
Electricity Price Spain (€/MWh)	49.21	0.03	101.99	14.35	−0.45	0.77	23.04	70.67
Electricity Price France (€/MWh)	42.84	−31.82	874.01	20.32	6.64	222.74	17.27	74.74
Price gap Spain-France (€/MWh)	6.38	−810.96	68.50	14.75	−14.83	741.26	−11.07	25.45
Exports (Spain- > France) (MWh)	399.74	0.00	3632.08	774.97	1.91	2.25	0.10	2286.46
Imports (France- > Spain) (MWh)	1597.84	0.00	3755.34	1053.14	−0.26	−1.21	0.00	3091.84
France net imports-exports (MWh)	1198.10	−3632.08	3636.90	1692.51	−0.97	−0.27	−2250.88	3057.39
France total imports + exports (MWh)	1997.58	127.75	4291.60	744.84	−0.18	−0.64	698.41	3153.28

more general problem of estimating the parameters of continuous-time jump processes from discretely sampled data; Cont and Tankov [23] offer an excellent review. Estimation procedures that involve the characteristic function, such as maximum likelihood (ML) estimation, are of particular interest from the viewpoint of statistical soundness. Below we will proceed in two steps. First we address the deterministic part of the price processes, and then their stochastic part. We stick with daily power prices in both countries.

3.3. Monte Carlo simulation of power prices

We simulate the stochastic part of the log prices by means of an Euler discretization of Equations (3) and (4):

$$X^i_{t+1} = X^i_t + \left(\alpha^i - \kappa^i X^i_t\right)\Delta t + \sigma^i\sqrt{\Delta t}\,\nu_i + \Delta q^i_j\left(\mu^i_j + \sigma^i_j x^i_j\right), \tag{6}$$

where $\Delta q^i_j = 1$ with probability $\lambda^i \Delta t$, and $\Delta q^i_j = 0$ with probability $1 - \lambda^i \Delta t$ (here $\Delta t = 1/365$). The Poisson behaviour is simulated with random numbers sampled from a binary distribution with jump probability $\lambda^i \Delta t$. When there is a jump its size is $\mu^i_j + \sigma^i_j x^i_j$, which is simulated with random numbers x^i_j from independent N(0,1) samples. This amounts to extracting the jump size from a normal distribution $N(\mu^i_j, \sigma^i_j)$.

Regarding the OU component, we generate random samples of correlated daily log prices for France according to this scheme:

$$\nu_S = x_S;\ \nu_F = \rho x_S + x_F\sqrt{1-\rho^2} \tag{7}$$

Here ν_S denotes samples of the third term in Equation (6) for Spain, while ν_F does so for France. Instead, x_S and x_F are two independent N(0; 1) samples. ρ is the correlation coefficient between the two stochastic parts, X^S_t and X^F_t.

3.4. Estimation of power flows along the interconnector

Drawing on historical hourly data (2016–2019, Table 1) we assume a maximum transmission capacity of 3500 MWh. Therefore, in our computations below, exports and imports are left-censored (i.e. censored from below) at a value of zero, and right-censored (i.e. censored from above) at 3500 MWh. Censoring' means that we observe the independent variables for all cases, but the dependent variable is observed only over a restricted range of values (not its entire range). Censoring does not change the sample, but involves loss of information in a systematic way. In our case, left-censored data are aggregated and included as 0s, and right-censored ones as 3,500s. Consequently, the standard Linear Regression Model provides inconsistent estimates of the parameters. Instead, the Tobit model provides consistent estimates (assuming, as usual, that the errors are normal and homoscedastic); it uses all of the information, including information about the censoring. Thus, ordinary least squares (OLS) must be replaced by ML estimation; see Long [24].

4. Data

Our data set includes daily and hourly information on domestic electricity spot prices (€/MWh) along with imports/exports (MWh) between Spain and France; it can be downloaded from the e-sios database (https://www.esios.ree.es/). The sample period is 2016–2019, i.e. four years. In particular, we have 1461 daily prices and 35,064 hourly prices. During this period the commercial interconnection capacity remained constant at 2800 MW.

The upper block in Table 1 shows descriptive statistics of hourly power prices. Spanish prices are 6.38 €/MWh higher than the French ones on average (= 49.21–42.84)[11]; the latter are more volatile than the former (20.32 €/MWh *vs* 14.35). Besides, the price gap between Spain and France shows negative skewness (−14.83), i.e. the left tail of the distribution is longer/fatter than the right one (in other words, the probability mass is concentrated on the right of the distribution). It also displays positive excess kurtosis (741.26), that is, extreme values are, well, more extreme than in a Normal distribution (whose kurtosis is 3); this is confirmed by the maximum (68.50), minimum (−810.96), and the 5% and 95% percentiles (−11.07 and 25.45, respectively).[12] Sizeable positive or negative price gaps contribute positively to the economic value of the interconnection with France.

The lower block provides information about actual power flows. For instance, maximum exports from Spain to France reach 3632.08 MWh, and 3755.34 the other way round. Thus, the maximum capacity of the interconnector is somewhat higher than 3500 MW, above its commercial capacity (2800 MW as already stated), because of an additional capacity devoted to SoS. Anyway, commercial capacity is not exactly constant (see Figure A4); it is periodically reset by Red Eléctrica de España (REE, the Spanish transmission system operator). During the sample period the net balance shows electricity flowing from France to Spain (at a rate of 1597.84–399.74 = 1198.10 MWh on average).

Table 2 shows some hourly price and quantity correlations. The

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[11] ACER (2020, Table 5) shows the average gap across the Pyrenees in 2016 (2.9 €/MWh), 2017 (7.3), 2018 (7.1), and 2019 (8.2). This price differential is not the same as the 'marginal value of transmission capacity' in Spiecker et al. (2017), which corresponds to the sum (or average) of absolute price differences between two regions over a year. In our sample period, the average absolute gap on this interconnector has been 9.78 €/MWh. As a reference, it was 11 €/MWh across the England-France interconnector for 2011–12; [14]. In the case of Spain-France, ACER (2020) provides yearly estimates in 2016 (8 €/MWh), 2017 (10.2), 2018 (10.8), and 2019 (10.1).

[12] Just to put these figures into context [8], analyse five pairs of European neighbouring countries. Absolute average hourly spreads range between 0.27 €/MWh and 15.56 €/MWh, with standard deviations from 17.76 to 40.75. The maximum spread is 915 €/MWh (between The Netherlands and UK), and the minimum spread is −901 €/MWh (between Germany and the Netherlands), both during peak hours.

Table 2
Hourly prices and power flows: Correlation coefficients (2016–2019).

	Electricity Price Spain	Electricity Price France	Price gap Spain-France	Exports (Spain- > France)	*Imports (France- > Spain)*
Electricity Price Spain	1.0000				
Electricity Price France	0.6878	1.0000			
Price gap Spain-France	0.0251	−0.7084	1.0000		
Exports (Spain- > France)	−0.0104	0.3747	−0.5261	1.0000	
Imports (France- > Spain)	0.0874	−0.2751	0.4639	−0.7075	1.0000

correlation between Spanish and French prices is 0.6878.[13] As expected, Spanish imports from France are positively correlated with the price gap between these countries (0.4639). At the same time, Spanish exports to France are negatively correlated with the price gap (−0.5261).[14] Thus, the price gap is a major driver of power flow along the interconnection with France.

Now, Table 3 shows descriptive statistics of daily electricity prices. The average price gap with France remains similar as with hourly prices (6.47 €/MWh). Not surprisingly, price gap volatility (10.79 €/MWh) is lower than with hourly ones (14.75). Daily prices also show positive excess kurtosis. The average daily net import from France is 28,754.37 MWh.

As seen in Table 4, the correlation between Spanish and French daily prices (0.7549) is a bit higher than with hourly prices; this lower hourly correlation can be explained by different seasonality in these countries (e.g. different hourly habits in consumer behaviour). The correlation between the price gap and power flows is 0.6709 for Spanish imports and −0.7500 for exports to France, both stronger than with hourly prices.

Fig. 1 displays daily prices in both countries. Most of the time French prices are cheaper than Spanish ones. Besides, in both countries price volatility is high. In Spain, the minimum price is lower than the average less three times the standard deviation ($1.94 < 49.21 - 3 \times 12.86 = 10.63$), while the maximum price in France is higher than the average plus five times the volatility ($125.67 > 42.83 + 5 \times 16.31 = 124.38$). Usually, whenever there is an abnormal peak (or the opposite) the starting price is more or less normal and then returns toward a normal level in the following day.

Fig. 2 shows the daily price gap between these countries. There is a seasonal pattern, with wider gaps in the summer and narrower ones in winter. Further information extracted from our sample data is available in Appendix A.

5. Estimation of the price model

Regarding the first seven parameters of the deterministic part, from Equation (2) and applying OLS we derive the estimates in Table 5. Some estimates are relevant for the value of the deterministic component. β_1^i and β_2^i in particular reveal a greater impact of annual seasonality for France. Others, such as β_3^S, have little influence.The estimates of the trend coefficients, $\beta_5^S = 0.0728$ and $\beta_5^F = 0.0454$, suggest that the price gap has been widening over time. This in turn translates into an increase in the economic value of the interconnection.

We have also derived numerical estimates of the parameters involved in hourly seasonality: $\beta_8^i, \ldots, \beta_{32}^i$, with $i = S, F$. For this purpose we calculate the difference between the (log) price in each hour of a day and the (log) price in that day. Thus, since the sample comprises 1461 days, we have 1461 differences for each of the 24 h. The average of those 1461 differences for, say, the first hour of the day, is the seasonality for that hour. The process is repeated for each of the remaining hours and separately for France and Spain. Thus, the numbers in Table 6 are to be interpreted with respect to the daily price (in a given day): a positive (respectively, negative) figure means an hourly price above (resp. below) the overall daily price (note that we use log prices).

As can be seen in Fig. 3, hourly seasonality shows wider variation in France, with peaks and troughs further away from each other than in Spain. Maximum hourly prices tend to happen around 20:00 in France and 22:00 in Spain; the minimum prices are usually reached about 5:00 in both countries. In France below-average prices are found from 1:00 till 7:00; in Spain they run until 8:00. These different hourly patterns can impact both export and import power flows between the two countries.

Upon estimation of $f^i(t)$ we can break the price process into its two components: deterministic and stochastic. The upper panel in Fig. 4 shows the (natural logarithm of) power price in Spain, $\ln(p_t^S)$, alongside its deterministic part, $f^S(t)$. The lower panel, instead, displays $\ln(p_t^S)$ with $f^S(t)$ removed, i.e. the stochastic part, X_t^S.

Similarly for France, the upper panel in Fig. 5 shows $\ln(p_t^F)$, alongside $f^F(t)$. Instead, the lower panel displays the stochastic component, X_t^F.

Concerning the stochastic part of the (natural logarithm of) power prices, X_t^i, we follow maximum likelihood estimation (see Appendix B) and obtain the parameter estimates in Table 7. On the other hand, the correlation coefficient between X_t^S and X_t^F is $\rho = 0.6570$. This is somewhat different from the one obtained with daily prices (0.7549), because it refers only to the stochastic parts of the (log) prices.

In Spain an average of 32.15 jumps are expected per year and 37.88 in France; thus, the daily ($\Delta t = 1/365$) jump probabilities are $\lambda^i dt = 0.0881$ and 0.1038, respectively. Jumps in Spain follow a normal distribution $N(\mu_j^S, \sigma_j^S) = N(\text{-}0.1347; 0.5462)$. In France they behave according to $N(\text{-}0.0973, 0.4431)$; this suggests negative, less pronounced, and less volatile jumps. However, in the absence of jumps, the log price in France is more volatile (2.4374) and tends to return faster (67.4638) to its long-term equilibrium value.

6. Monte Carlo simulation of power prices

Our numerical application of the scheme in Equation (7) generates 10,000 correlated random samples with $\rho = 0.6574$, very close to the estimated value of 0.6570. We run 10,000 simulations for three years (2020, 2021 and 2022), i.e. 1096 days, under the real-world probability measure.

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[13] [29] estimate a correlation of 0.6524 based on 81 monthly price observations between 2004 and 2011. Both figures are similar to the correlation (0.67) between hourly prices in France and the UK from November 2001 through June 2009 found by Ref. [8].

[14] These signs are consistent with results in Ref. [36]. Drawing on monthly data for 29 European countries they find that power price (as an explanatory variable of net exports) is statistically significant in most of their specifications; it has a negative impact, i.e. decreasing domestic prices make net exports more appealing. Interestingly for our case, they also find that, on average, neighbouring countries (Spain) of “large” countries (France) are positive net importers (admittedly, at low orders of magnitude).

Table 3
Daily prices and power flows: Descriptive statistics (2016–2019).

	Mean	Minimum	Maximum	Standard Deviation	Skewness	Excess Kurtosis	Percentile 5%	Percentile 95%
Electricity Price Spain (€/MWh)	49.21	1.94	91.88	12.86	−0.52	0.87	25.41	68.01
Electricity Price France (€/MWh)	42.83	2.66	125.67	16.31	0.99	1.98	20.86	70.89
Price gap Spain-France (€/MWh)	6.47	−68.04	50.87	10.79	−0.99	5.41	−9.53	21.90
Exports (Spain- > France) (MWh)	9593.75	0.00	71,261.77	15,472.64	1.80	2.22	2.60	47,360.50
Imports (France- > Spain) (MWh)	38,348.12	0.00	78,997.68	21,106.50	−0.23	−0.99	1369.82	70,036.63
France net imports-exports (MWh)	28,754.37	−70,673.92	78,994.02	34,564.26	−0.95	−0.08	−44,301.98	69,326.31
France total imports + exports (MWh)	47,941.86	15,596.54	81,699.32	13,231.98	0.19	−0.63	27,997.47	71,082.50

Table 4
Daily prices and power flows: Correlation coefficients (2016–2019).

	Electricity Price Spain	Electricity Price France	Price gap Spain-France	Exports (Spain- > France)	*Imports (France- > Spain)*
Electricity Price Spain	1.0000				
Electricity Price France	0.7549	1.0000			
Price gap Spain-France	0.0465	−0.6171	1.0000		
Exports (Spain- > France)	−0.0605	0.4457	−0.7500	1.0000	
Imports (France- > Spain)	0.1420	−0.3266	0.6709	−0.7805	1.0000

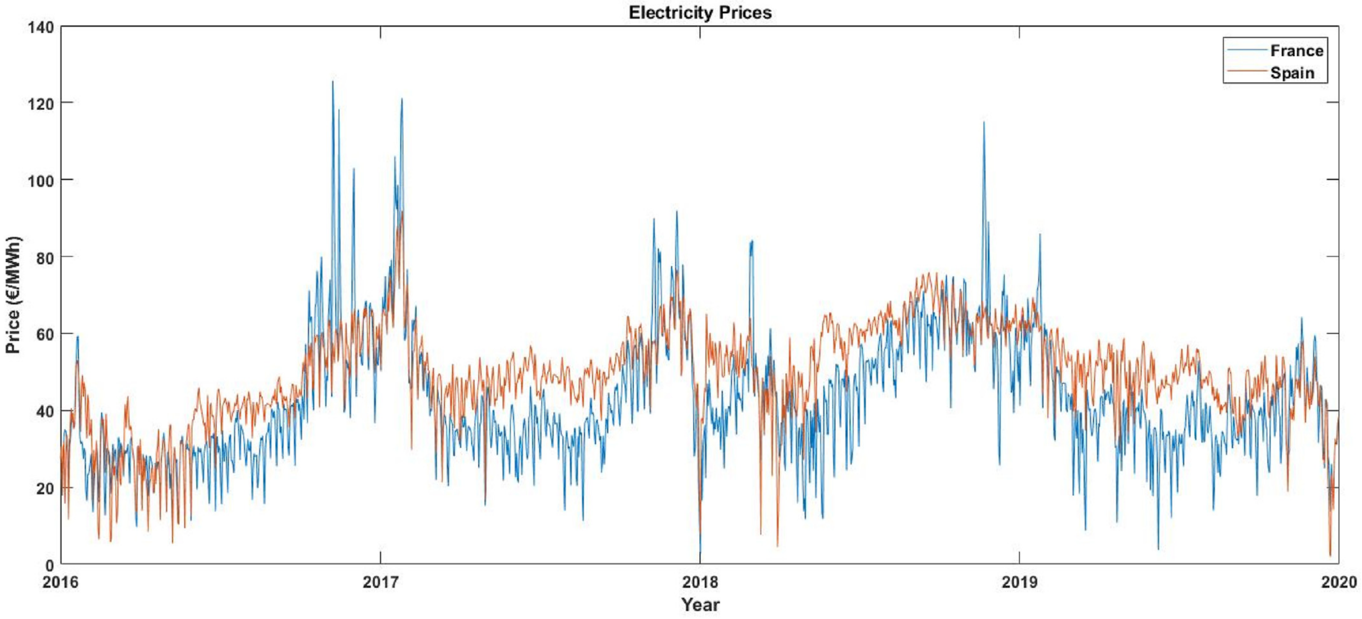


Fig. 1. Daily spot electricity prices in France and Spain, 2016–2019.

Starting with Spain, initially we simulate the stochastic daily part, X_t^S using Equation (7). In a second step we add the deterministic daily part, $f^S(t)$, according to Equation (1), with the annual and semi-annual seasonalities, trend, effects of weekend and non-working days, and a constant. Finally, we transform the log prices into absolute prices (in €/MWh). Fig. 6 shows the historical path of the daily log price over 2016–2019 along with a simulated path for 2020–2022 and the deterministic part alone.

As before, we add the deterministic part to X_t^F and finally come up with simulated paths of daily power prices for France. Thus, we have 10,000 simulated paths of future daily prices in each country. Hence we can compute 10,000 daily price gaps between these countries for every single day over the period 2020–2022. Fig. 7 displays the average of 10,000 daily gaps in any day during this period. The gap shows a seasonal behaviour; the same applies to the observed price gap (see Fig. 2).

Next, we transform the simulated daily log price series, $\ln(p_t^i)$, into hourly series by applying the hourly seasonality coefficients (Table 6) to each of the former series (thus obtaining 24 log prices for each day); the log prices are further translated into absolute prices (€/MWh). Finally, we compute the hourly price gaps over 2020–22, namely $24 \times (366 + 365{+}365) = 26{,}304$ hourly gaps for each of our 10,000 simulations, i.e. 10,000 hourly paths of 26,304 values each. Fig. 8 shows the resulting probability distribution. The 10% percentile is −13.63 €/MWh while the 90% percentile is 39.19 €/MWh. The average is 13.65 and the median a bit higher, namely 13.88 €/MWh. The distribution displays negative skewness.

7. Power flows along the Spain-France interconnector

Based on the 35,064 hourly observations for Spain, we estimate a Tobit model for exports to France and another one for imports

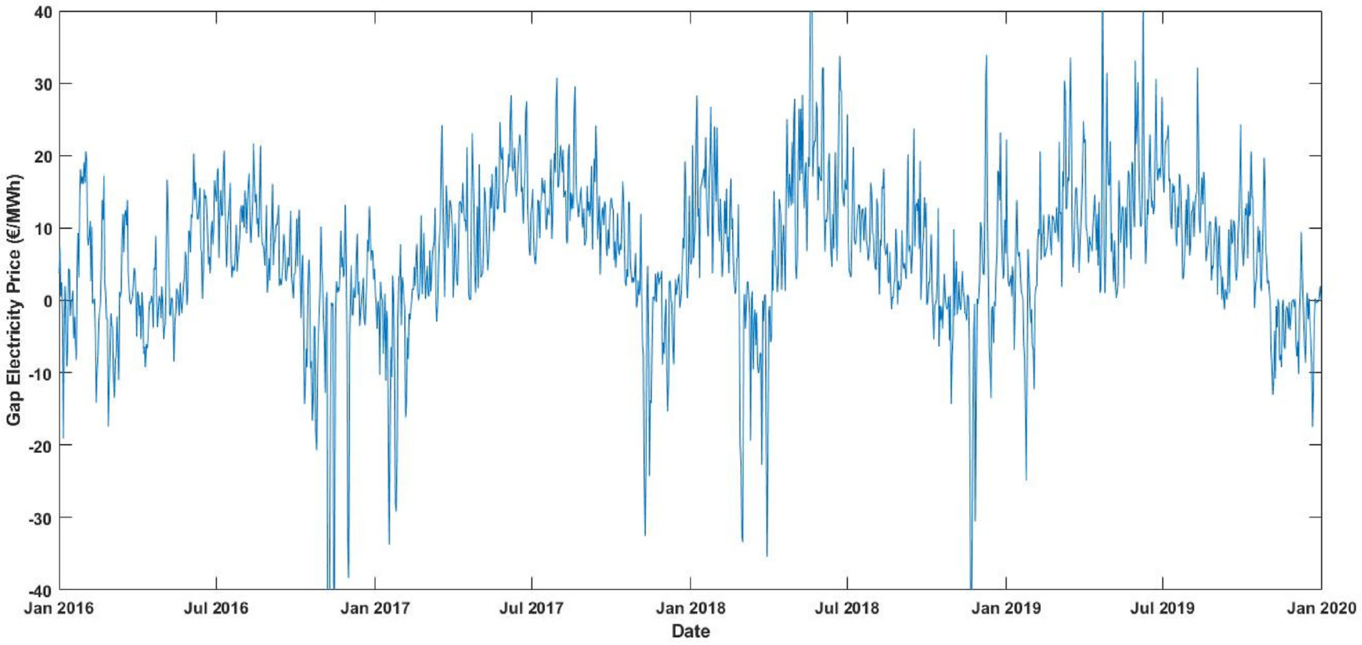


Fig. 2. Daily power price gap between Spain and France, 2016–2019.

Table 5
Parameter estimates of price processes (2016–2019, daily data): deterministic part $f^i(t)$, as shown in Eq. (2).

Parameter	Spain (i = S)	France (i = F)
β_1^i	−0.1288	−0.1597
β_2^i	0.0350	0.2081
β_3^i	−0.0007	−0.0329
β_4^i	0.0662	0.0206
β_5^i	0.0728	0.0454
β_6^i	−0.1770	−0.3233
β_7^i	3.7569	3.6939

from France. Tables 8 and 9 show the results from STATA, respectively.

Regarding Spanish exports, the likelihood ratio (LR) chi-square with p-value = 0.0000 informs us that the Tobit model is significantly better than an empty model. The coefficients are statistically significant. The/sigma statistic (671.7724) is the estimated standard error of the regression. With the numerical estimate of the price gap coefficient (−28.06604) we simulate power exports to France under uncertainty: Exports (S→F) = 564.46−28.06 × simulated gap + N(0; 671.77).

As for Spanish imports, again the LR tells us that the Tobit model is significantly better than an empty model. The coefficients are statistically different from zero. The estimated standard error of the regression in this case is 958.8273. We use the gap coefficient (53.39729) to simulate power imports from France under uncertainty.

8. Simulated transmission income to the interconnector

Power flows from one country to the other give rise to a monetary income (congestion rent) the size of which depends on the price gap between them. At the same time, we assume transmission costs of 5 €/MWh (as in Ref. [25]; or [8]. Thus, sometimes the net income can be negative because of this transmission cost. Nonetheless, it can also be negative because there can be exports when the gap price is positive (i.e. power flows from Spain to France despite its higher price in Spain), the same way that there can be imports when the gap is negative (that is, Spain purchases power

Table 6
Parameter estimates of price processes (2016–2019, daily data): deterministic part $f^i(t)$, hourly seasonality in Eq. (2).

Spain				France			
Hour	β_h^S	Hour	β_h^S	Hour	β_h^F	Hour	β_h^F
1:00	−0.0237	13:00	0.0471	1:00	−0.0906	13:00	0.0551
2:00	−0.1154	14:00	0.0401	2:00	−0.1990	14:00	−0.0056
3:00	−0.1838	15:00	0.0084	3:00	−0.2747	15:00	−0.0675
4:00	−0.2274	16:00	−0.0324	4:00	−0.3868	16:00	−0.0941
5:00	−0.2463	17:00	−0.0438	5:00	−0.4277	17:00	−0.0735
6:00	−0.2075	18:00	−0.0090	6:00	−0.3143	18:00	0.0455
7:00	−0.1163	19:00	0.0385	7:00	−0.1271	19:00	0.1802
8:00	−0.0177	20:00	0.0887	8:00	0.0432	20:00	0.2281
9:00	0.0334	21:00	0.1206	9:00	0.1187	21:00	0.1640
10:00	0.0693	22:00	0.1324	10:00	0.1315	22:00	0.0804
11:00	0.0713	23:00	0.0872	11:00	0.1014	23:00	0.0884
12:00	0.0575	24:00	0.0153	12:00	0.0861	24:00	0.0132

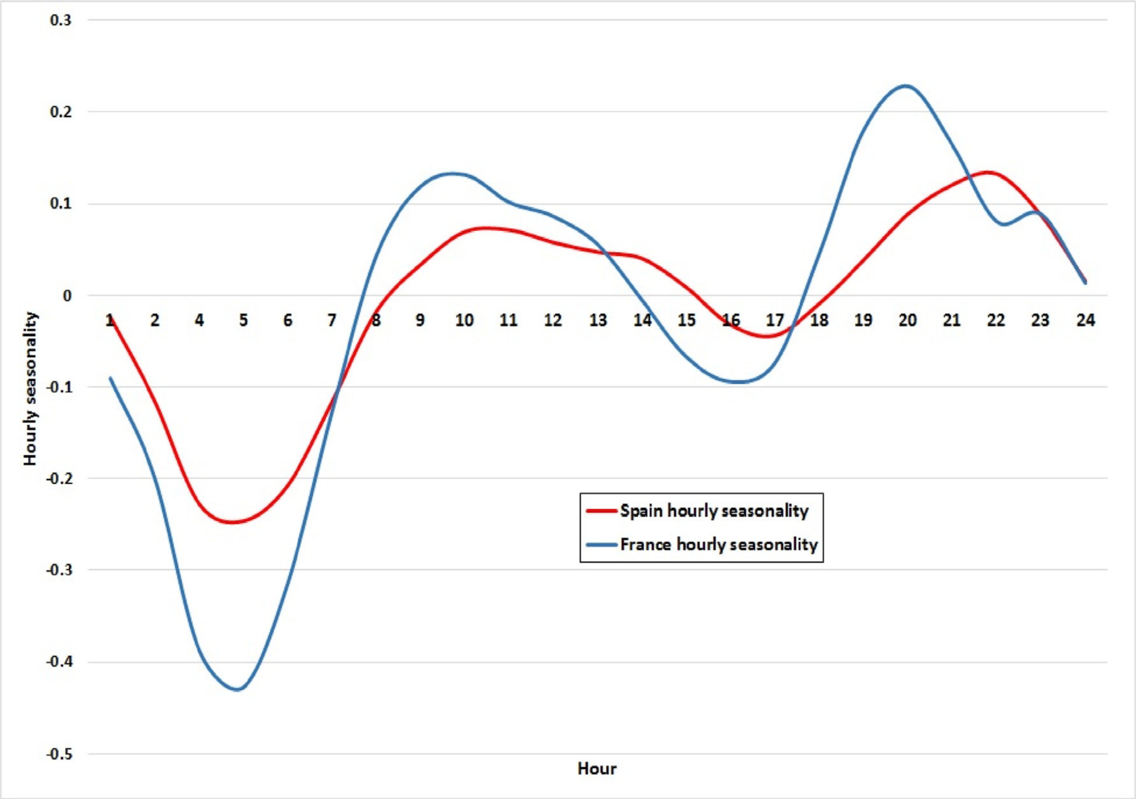


Fig. 3. Log price of electricity in France and Spain (2016–2019, hourly data): hourly seasonality (the average of the difference between the log price in each hour of a day and the log price in that day).

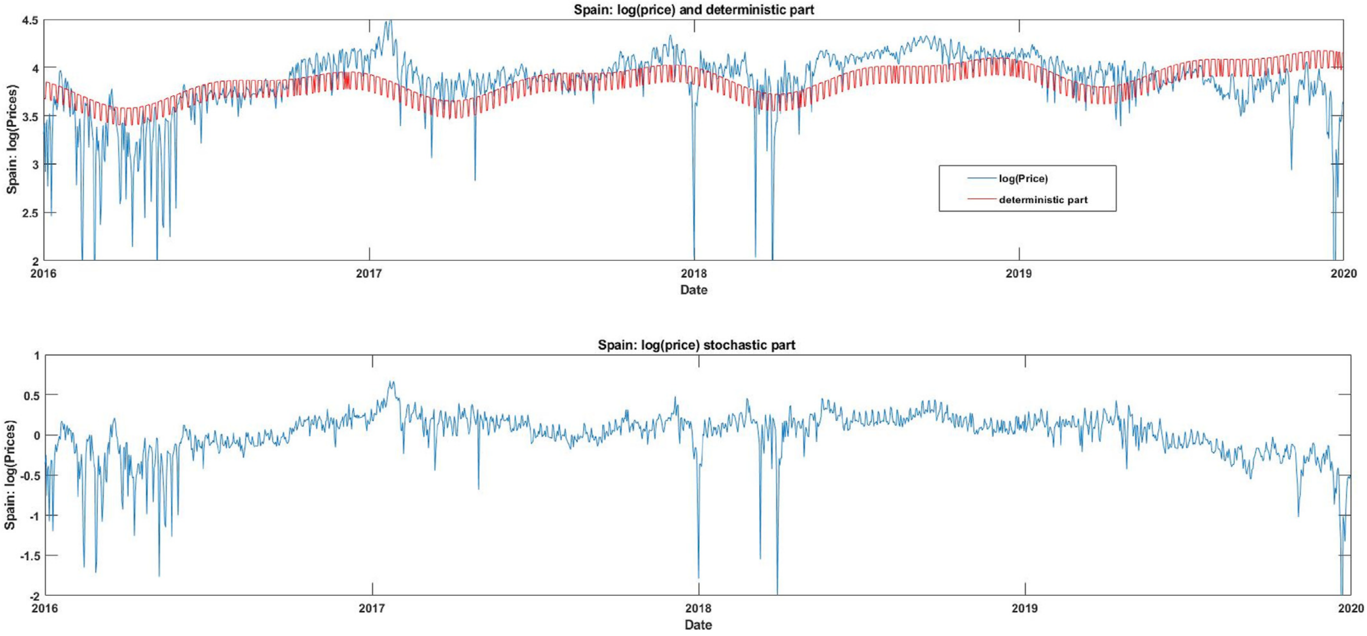
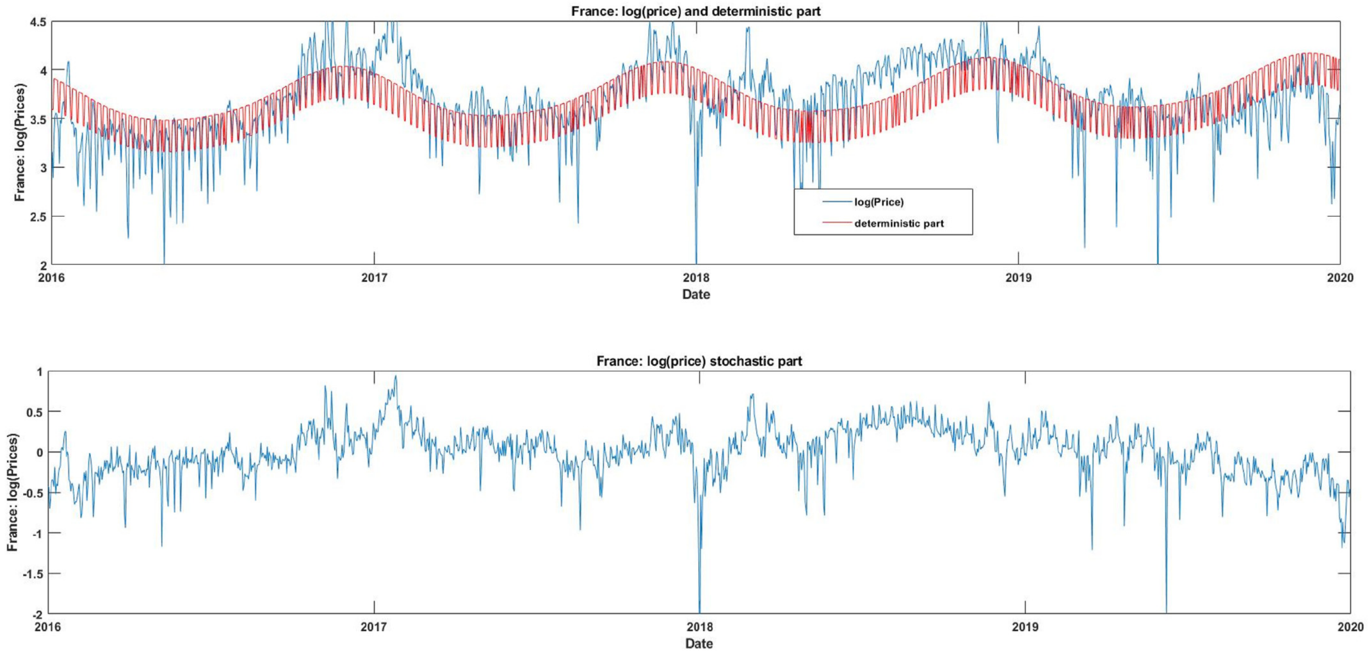


Fig. 4. Log electricity price in Spain (2016–2019, daily data): deterministic and stochastic parts.

from France in spite of higher prices there). This behaviour emanates from the actual behaviour reflected in the Tobit model (excluded 1073 + 3433 negative observations; the 96 observations above 3500 are censored). Fig. 9 displays the probability distribution of cumulative revenues and expenses (from the viewpoint of Spain) over the simulation horizon.

Table 10 shows a few basic descriptive statistics of the 3-year transmission income. Power exports generate an average of €27 million over 2020-22 while imports entail expenses of €964 million on average during the same period. The value of bilateral


France: log(price) and deterministic part

France: log(price) stochastic part

Fig. 5. Log electricity price in France (2016–2019, daily data): deterministic and stochastic parts.

Table 7
Parameter estimates of price processes (2016–2019, daily data): stochastic part X_t^i, Eqs. (3) and (4).

Parameter	Spain		France	
	Value	95% confidence interval	Value	95% confidence interval
α	4.3161	2.2018–6.4304	3.7019	0.8469–6.5568
κ	56.3486	46.2128–66.4844	67.4638	56.9641–77.9635
μ_j	−0.1347	−0.2378–−0.0316	−0.0973	−0.1842–−0.0105
σ	1.8261	1.7266–1.9205	2.4374	2.2788–2.5862
σ_j	0.5462	0.4547–0.6244	0.4431	0.357–0.515
λ	32.1534	23.7531–40.5537	37.8801	24.1242–51.636

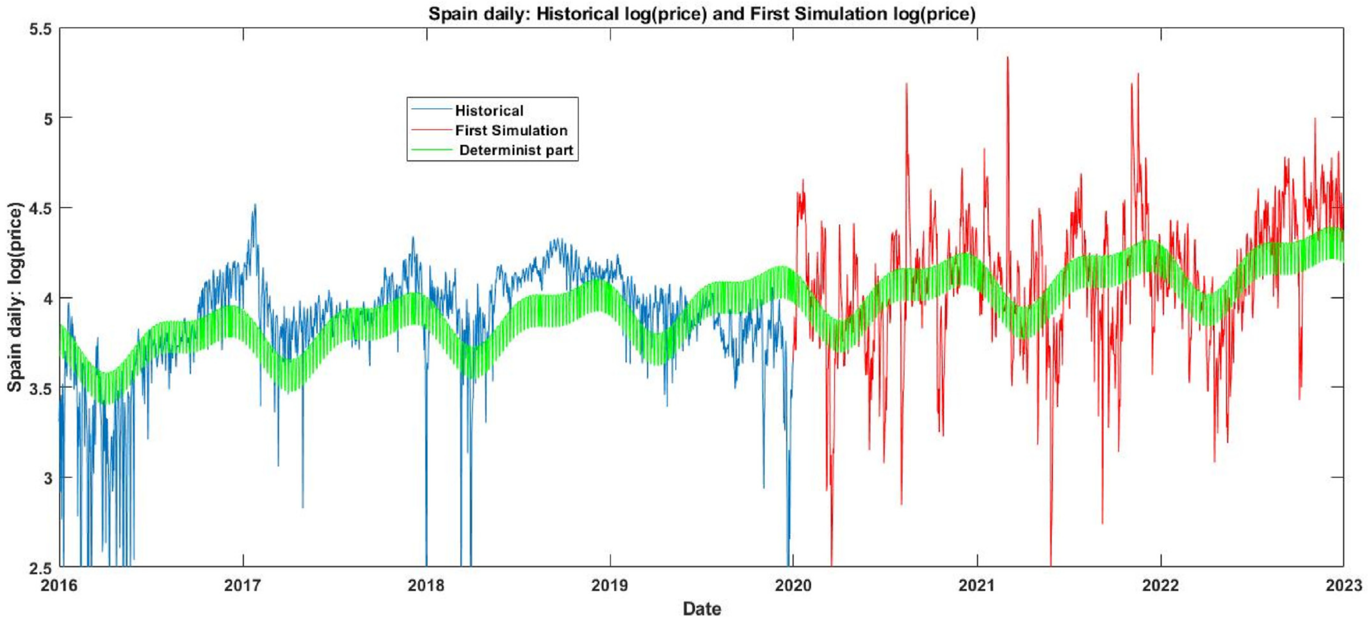

Spain daily: Historical log(price) and First Simulation log(price)

Fig. 6. Actual daily log price of electricity in Spain (2016–2019) and a simulated stochastic path (2020–2022).

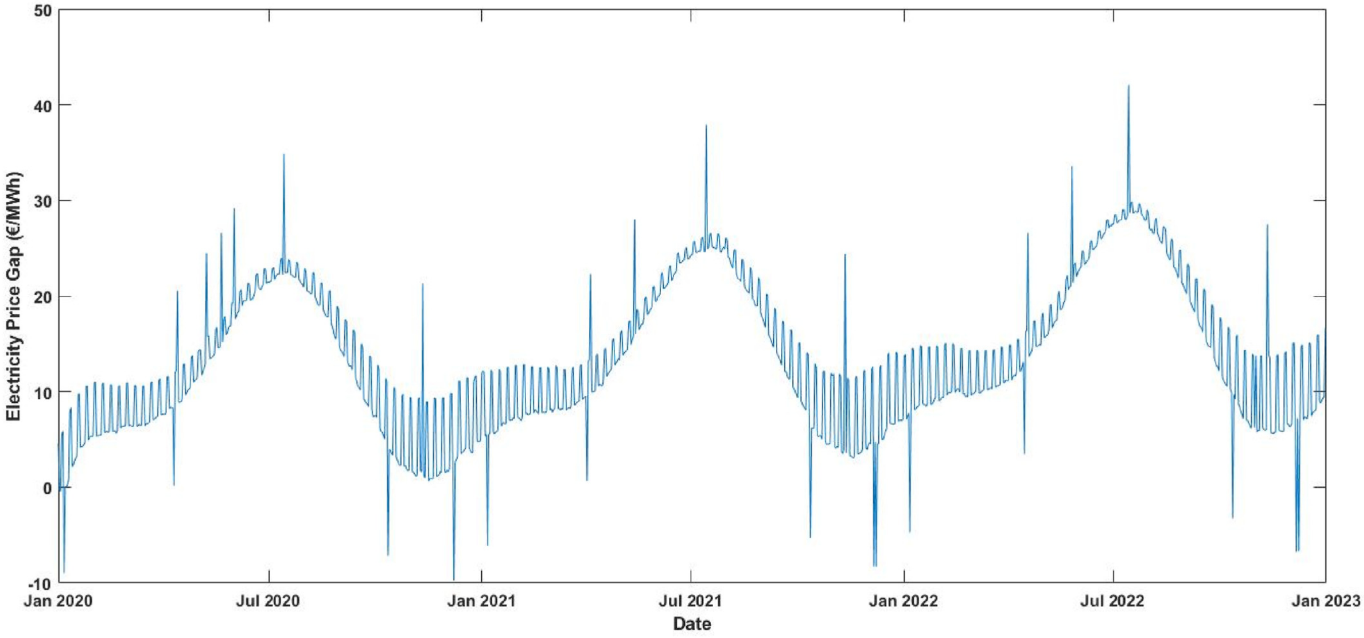


Fig. 7. Average of simulated daily price gaps between Spain and France (2020–2022).

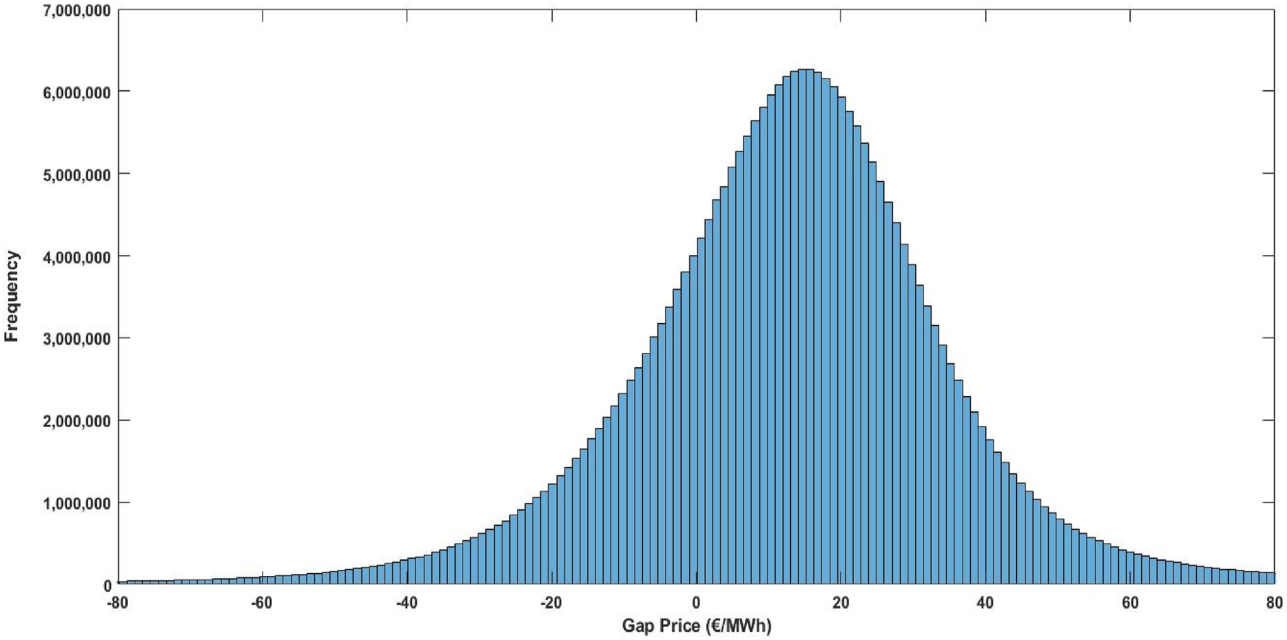


Fig. 8. Histogram of simulated hourly price gaps between Spain and France (2020–2022).

trade over this period thus amounts to €991 million. This implies an average of €330.3 million per year for a capacity of 3500 MW, or about €94 million/GWyr. Broadly comparable analyses are sparse. Meeus [26] addresses the 600 MW Kontek HVDC link between East Denmark and Germany under different market-coupling settings (from no coupling to one-way coupling, through approximate coupling).[15] The estimated welfare gain from coupling on that line is about €17 million/GWyr. On the other hand, SEM Committee [25] analyses the two interconnectors between Great Britain and the island of Ireland. In this case, the social welfare gain is estimated at €32 million/GWyr. On the other hand, ACER [4] looks at price differences across a sample of cross-border links. Considering the top 15 interconnectors, the average day-ahead arbitrage benefits for a 1000 MW link amount to €68 million/yr, able to justify substantial new investment [5]; drawing on this result, for a 3500 MW link the revenue would rise to €238 million/yr. Looking far into the future, in the year 2050 the congestion rent from the interconnector jumps from 1242 M€ with low interconnection capacity (1400 MW) to 2556 M€ with high interconnection capacity (21,500 MW);

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[15] 'Coupling' means that wholesale electricity prices should be equalized across boundaries unless the interconnector is constrained (in which case, prices can diverge but the interconnector should be fully utilized); [14].

Table 8
Tobit regression: Power flows from Spain to France (hourly data, 2016–2019).

					Number of obs =	35,064
					LR chi2(1) =	11,244.66
					Prob > chi2 =	0.0000
Log likelihood = −270,381.02					Pseudo R2 =	0.0204
Export	Coefficient	Std. Err.	T	P>|t|	[95% Interval]	
Price gap	−28.06604	0.2437418	−115.15	0.000	−28.54378	−27.5883
Constant	564.4652	3.919129	144.03	0.000	556.7836	572.1468
/sigma	671.7724	2.58251			666.7106	676.8342

1073 left-censored observations with exports to France = 0.
33,988 uncensored observations.
3 right-censored obs. with exports >3,500 MWh

Table 9
Tobit regression: Power flows from France to Spain (hourly data, 2016–2019).

					Number of obs =	35,064
					LR chi2(1) =	13,072.98
					Prob > chi2 =	0.0000
Log likelihood = −264,781.42					Pseudo R2 =	0.0241
Import	Coefficient	Std. Err.	T	P>|t|	[95% Interval]	
Gap Price	53.39729	0.4412728	121.01	0.000	52.53238	54.2622
Constant	1194.734	6.056656	197.26	0.000	1182.863	1206.606
/sigma	958.8273	3.895733			951.1916	966.4631

3433 left-censored observation with imports from France = 0.
31,538 uncensored observations.
93 right-censored obs. with imports >3500 MWh

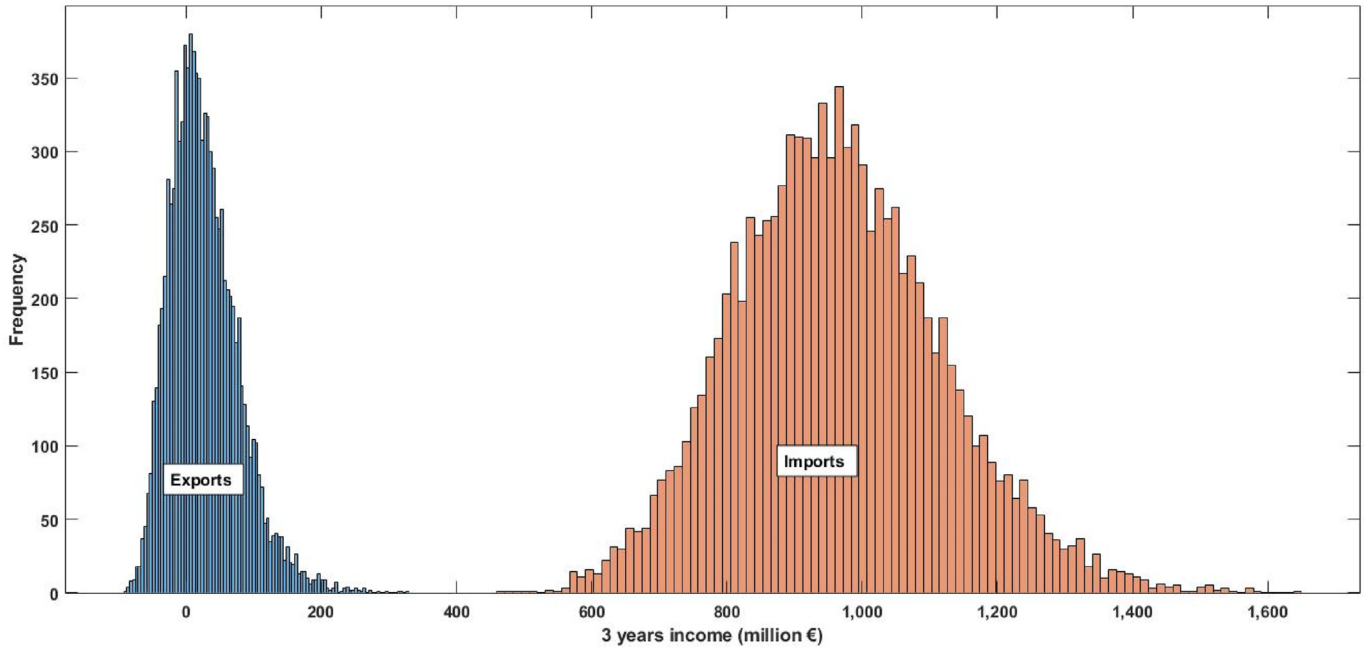

Fig. 9. Histogram of the simulated transmission income to the interconnector (2020–2022).

Table 10
Simulated 3-year income (million €) from cross-border power flows.

	10% percentile	Average	Median	90% percentile
Exports (S→F)	−32	27	20	94
Imports (F→S)	773	964	957	1166

In Europe, cross-border transmission investment projects are usually taken on the basis of commercial profitability, following a regulatory test that confirms positive contribution to social welfare; Konstantelos et al. [27]. To the extent that high transmission income is an indication of capacity constraint, the figures in Table 10 raise the business case for a reinforcement project Pudjianto et al. [11].

Table 11
Parameter estimates of price processes (2016–2019, daily data): zero growth ($\beta_5^i = 0$).

Parameter	Spain (i = S)	France (i = F)
β_1^i	−0.1520 (−0.1288)	−0.1741 (−0.1597)
β_2^i	0.0352 (0.0350)	0.2082 (0.2081)
β_3^i	−0.0122 (−0.0007)	−0.0401 (−0.0329)
β_4^i	0.0664 (0.0662)	0.0208 (0.0206)
β_5^i	–	–
β_6^i	−0.1770 (−0.1770)	−0.3230 (−0.3233)
β_7^i	3.9024 (3.7569)	3.7846 (3.6939)

between the two systems.[16] Further, as Konstantelos et al. [28] point out, the increasing penetration of variable renewable energy sources is noticeably expanding cross-border arbitrage opportunities.

In addition to the direct impacts in terms of expenses and revenues there can also be other indirect effects from increased cross-border competition. Newbery et al. [14] mention some of them: pressure to reduce costs, innovate, enhanced market liquidity, improved sustainability (if low-carbon power displaces more polluting sources), greater SoS, etc.

9. Sensitivity analysis

As shown in Equation (2), the (log) power price in each country depends on calendar time. Indeed, from our sample period 2016–2019 we estimated $\beta_5^S = 0.0728$ and $\beta_5^F = 0.0454$; see Table 5. These figures imply that not only domestic prices grow over time but the price gap as well, since $\beta_5^S > \beta_5^F$. Now, however, we impose zero growth, i.e. we adopt $\beta_5^S = \beta_5^F = 0$. Under this assumption, the remainder estimates of parameters change as shown in Table 11 (earlier figures in parenthesis for convenience). None of the changes is dramatic; a fraction of the impact previously attributed to the time trend shows up now through other (mainly seasonal) parameters.

On the other hand, the correlation coefficient between X_t^S and X_t^F is also slightly different: $\rho = 0.6687$ (instead of 0.6570 earlier). From Equation (6) this coefficient affects the correlated samples to use in the simulation. Upon generating 10,000 samples the resulting correlation is 0.6690, almost the same as the estimated value 0.6687.

As seen in Fig. 10, setting the two price trends equal (= 0) pushes the probabilistic mass to the left, thus reducing the average price gap. This goes in hand with a slight increase in its frequency.

At the same time, there is no change in the results from the Tobit regression model. Note that we are just estimating the model with exactly the same sample data (2016–2019) as before. However, the assumption of no price growth over time does impact the income to be collected from the cross-border transmission line. Table 12 displays some basic descriptive statistics.[17] For convenience, we also show the previous values.

Now, on average power exports generate up to €40 million over 2020–22 (a 48.15% increase). Imports remain much higher as before, and imply average expenses of €462 million in the same period (a 52.07% decrease). The overall pattern is clear: under the zero-growth assumption, Spain exports more power to France and imports less from its neighbour. In view of our earlier estimates (β_5^S=0.0728, $\beta_5^F = 0.0454$) this is not surprising: the upward trend of power price is stronger in Spain than in France. By suppressing this trend, Spain comparatively improves its competitiveness. This naturally leads to exporting more and importing less.

10. Conclusions

This paper falls within the literature on power transmission expansion in general and interconnector economics in particular. The focus here is power trade based on price differentials. Standard approaches draw on (deterministic) optimization models where the electricity price is one of the variables determined in the process (i.e. it is endogenous). In those papers the power price is hardly the main focus; typically there is nothing said about the extent to which the resulting price series display the observed dynamics of electricity price in actual markets.

Now, the paper at hand introduces a new approach for quantifying the potential revenue to a cross-border interconnector. Our approach brings the (spot) price to the forefront of the analysis while accounting for its usual properties in practice: uncertainty, seasonality, mean reversion, jumps, and correlation across countries. We use the price model along with an econometric model of power exports and imports to assess the economics of an interconnector.

The second contribution of our paper is an empirical application to a singular cross-border interconnector. The Iberian peninsula shows relative electrical insularity within Europe. Spain in particular has an interconnection ratio (2.8% in 2019) that is far lower than the EU minimum goal (10% for 2020 and 15% for 2030). The interconnection with France is thus extremely important, since it gives access to the vast European power market. A new project, already under way, is expected to start operation in 2024 or 2025. Upon completion, it will raise Spain's interconnection ratio to about 5%, still well below the stated EU minimum goals.

We find that Spanish exports amount to €27 million on average over the three-year period 2020–22; imports from France entail average expenses of €964 million. Bilateral trade over this period, €991 million, implies €330.3 million on average per year for a capacity of 3500 MW, i.e. about €94 million/GWyr. These values are much higher than others found in the literature. Thus, Meeus [26] estimates the social welfare gain from coupling on a link between East Denmark and Germany of about €17 million/GWyr. In the case of the two interconnectors between Great Britain and the island of Ireland, that gain is estimated at €32 million/GWyr; SEM Committee [25]. Drawing on the top 15 interconnectors in ACER [4]; for a 3500 MW link the revenue would rise to €238 million/yr. On the other hand, our sensitivity analysis shows that, when we impose the restriction of no growth in domestic power prices, the trade balance for Spain improves, since the upward trend in price is stronger in Spain than in France. These results are potentially useful for power producers, traders, and consumers. They are also useful for policy makers, e.g. regarding the potential role of load shifting for reducing congestion [9], the integration of renewables by reducing curtailment [11], or the distributional impacts of public policies via the power price [17].

This said, several qualifications are in order. First, alternative approaches are possible. Thus, as Cartea and González-Pedraz [8] point out, the owner of an interconnector has the right, but not the

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[16] Note that, as Spiecker et al. (2017) point out, the optimal transmission capacity is not the one that avoids all welfare losses of congestion, since these must be set against the investment cost of newly built transmission lines (which we leave aside). Similarly, we are overlooking here that, according to Ref. [37]; the current interconnector capacities are insufficient to prevent large national utilities from exercising market power without proper regulation, which can impact their fondness for new lines.

[17] The histograms of income from power exports/imports are available from the authors upon request.

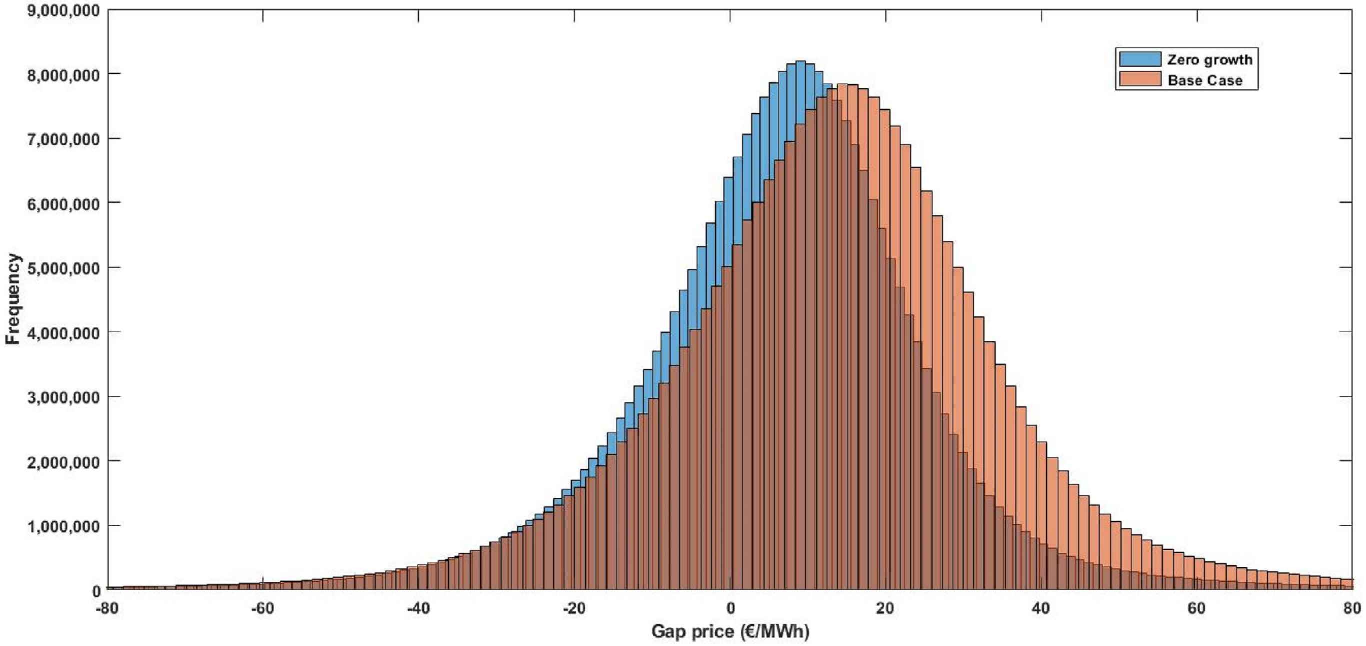

Fig. 10. Histogram of simulated hourly price gaps between Spain and France (2020–2022).

Table 12
Simulated 3-year income (million €) from cross-border power flows: zero price growth.

	10% percentile	Mean	90% percentile
Exports (S→F)	−18 (−32)	40 (27)	105 (94)
Imports (F→S)	333 (773)	462 (964)	600 (1166)

obligation, to transmit power between two markets. Therefore, once it has been built, the financial value of an interconnector is given by a series of real options written on the spread between the power prices in these markets.

Regarding prices, policy measures to promote variable renewable generation sometimes interfere with cross-border trade by distorting price formation in domestic markets; Bahar and Sauvage [29].[18] Further, differences in support schemes in the interconnected countries and/or the way they deal with negative prices can give rise to artificial differences between their wholesale prices.

From a quantity-based viewpoint, the further deployment of renewable technologies calls for expanded cross-border connections (to avoid congestion of the interconnectors and the ensuing loss of cross-border capacity available to market participants). Even when sizeable portions of aggregate congestion arise in specific regions, international cooperation turns out to be valuable for congestion management; Kunz and Zerrahn [30]. As a matter or circularity, cross-border power trade in turn has a significant and positive impact on the effective capacity factor of wind parks, for example; OECD [31].

In addition, different national approaches to the role of intermittent generators in balancing responsibilities can leave their mark on cross-border electricity trade. Another issue that goes beyond technical aspects has to do with unscheduled power flows. According to Kunz [15]; they are a by-product of the European approach to congestion management. National market arrangements can also have an impact on cross-border trade, among them: gate-closure times (before the real-time dispatch of electricity),[19] the rules and design of power markets, auctions, and transmission fees.

We leave these issues aside. Nevertheless, the implications for policy makers are clear: if an efficient, integrated European power market is ever to exist, then it is necessary to advance in common toward a greater harmonization on a number of dimensions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121177.

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[18] Other generating technologies too receive direct and/or indirect forms of support, which can similarly distort price formation.

[19] Gate-closure time in France is 60 min before delivery. In Spain there are 6 gate-closure times during the day; [29].

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