The impact of electricity market integration on the cost of CO_2 emissions abatement through renewable energy promotion[*]

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Abstract

The integration of electricity markets is widely promoted for its positive impact on competition and energy security. However, little is known about its consequences on emissions and the optimal deployment of renewable energies. In this paper, I utilize the sudden and substantial expansion of the Spanish-French electricity interconnector to causally estimate the impact of integration on the quantity and localization of CO_2 emissions avoided by Spanish wind production, as well as its impact on the electricity prices of both countries. I find that integration has increased the amount of emissions avoided in France but decreased that avoided in Spain for each additional megawatt-hour of Spanish wind. The increase in France does not offset the decrease in Spain, resulting in a lowered environmental value of Spanish wind. For the effect on prices, the previously non-significant impact on French prices before the expansion becomes significant afterwards, highlighting a cross-border merit order effect. I then calculate the cost of reducing one ton of CO_2 for the Spanish consumer through the wind energy subsidy program. Due to the price effect, there is a net gain of 26.1€/tCO_2 which was reduced to 3.6€/tCO_2 following the expansion. On the other hand, the French consumer benefits for free from the abatement of 2 megatonnes of CO_2 annually, financed at a cost of 143€/tCO_2 by the Spanish taxpayer post expansion. This suggests that the current operation of the markets might incentivize freeriding on neighboring countries' subsidies for renewable electricity. Finally, I calculate the marginal impact of wind generation on welfare, taking into account the decrease in electricity generators' profits due to the price effect and the gains related to emissions abatement. The subsidy policy is welfare improving starting from a social cost of carbon of 60€/tCO_2 pre-expansion and 70€/tCO_2 post-expansion.

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1 Introduction

Integrating national electricity markets by expanding cross-border electricity interconnection capacity offers many significant advantages. Relaxing transmission constraints enhances competition and reduces gaming incentives (Borenstein et al., 2000), fosters price convergence among connected regions (Horst Keppler et al., 2016), and facilitates cost-effective dispatch of existing generation capacities across regions (Brunekreeft et al., 2005). According to the Agency for the Cooperation of Energy Regulators (ACER, 2022), the benefits associated with improving the integration of European electricity markets over the past decade are estimated at 34 billion euros annually. These benefits, along with the imperative to foster competition in electricity markets, are a strong argument for the needs for further developments in interconnections.

While the above benefits are undeniable, the integration of national electricity markets also has less clear implications when it comes to assessing the environmental and market value of renewable energy built in a country with interconnector capacity to another. Recent literature has begun to explore these nuanced issues. Empirical studies have assessed how increased electricity interconnection between a region with significant renewable capacity and another with polluting thermal generation impacts emissions and market prices (Fell et al., 2021; Gonzales et al., 2022). However, there is limited evidence for cases where two regions, and especially two countries, with polluting generation are connected.

This paper studies the impact of a sudden increase in interconnection capacity between France and Spain, two countries that both have thermal generation and renewable energy, on the value of renewable electricity. Specifically, I estimate the impact of the 2015 expansion of the interconnection between France and Spain on a) the environmental value of the Spanish wind energy and b) the electricity prices in the two countries. The environmental value of renewable energy is defined as the number of tons of CO_2 emissions avoided per additional megawatt-hour of renewable energy generated. Throughout this paper, I refer to this concept as 'the environmental value of renewable energy' or 'the marginal abatement effect of CO_2'.

While wind energy, whose marginal cost is close to zero, substitutes for polluting electricity generation in the country of origin, cross-border interconnectors can generate spillover effects that mitigate the substitution effect and lead to a shift to the interconnected country. The sudden and substantial expansion of Spanish-French interconnection capacity allows me to causally estimate how market integration shifts the CO_2 marginal abatement effect of Spanish wind energy on Spanish emissions and the cross-border marginal abatement effect of the same wind energy on French emissions.

Additionally, I explore the influence of the interconnection on the merit order effect and cross-border merit order effect of Spanish wind energy, i.e., the impact of wind energy on electricity prices in Spain and France. I assemble data from the French and Spanish electricity markets which combines hourly generation at the technology level, emissions, fuel prices, CO_2 prices, weather conditions and a measure of country's overall economic output from 2014 to 2016. Technically, I employ a Regression-Discontinuity-in-Time approach. This quasi-experimental design enables me to measure the local treatment effect while accounting for the possibility that my outcome variable would have changed smoothly around the treatment date in the absence of treatment. A challenge with identifying the merit order effect and cross-border merit order effect of Spanish renewable energy is the reverse causal relation between load and prices. To circumvent this challenge, I apply IV-techniques leveraging variation in temperature, industrial production and hours of daylight at the country level. Our analysis thus employs a similar strategy to Grossi et al. (2017).

The main results of my study are the following. Firstly, doubling the interconnection capacity between the two countries has reduced the domestic CO_2 marginal abatement effect of Spanish wind energy by 30%, from 0.573 tCO_2/MWh to 0.398 tCO_2/MWh because of less coal generation offset. For context, the average CO_2 emissions from the Spanish electricity mix over the given period amount to 0.215 tCO_2/MWh. Therefore, the environmental value of wind power is still higher than the average emissions. Conversely, it has increased the cross-border CO_2 marginal abatement effect of Spanish wind generation on French emissions from 0.006 tCO_2/MWh to 0.045 tCO_2/MWh, thereby compensating part of the domestic decrease, but not all of it. It means that even when accounting for the emissions avoided across the border, market integration has resulted in a decrease in the environmental value of Spanish wind energy.

Secondly, I show how the effect of Spanish wind energy on electricity wholesale prices has changed due to the expansion of the interconnector. Prior to the expansion of the interconnection capacity, an additional gigawatt-hour of wind energy generated in Spain led to an average decrease in electricity prices of €2.7 per MWh in Spain and €0.12 per MWh in France, respectively. These values represent 5 and 0.3 percent of the average wholesale price over the period. Following the expansion of this interconnection, the domestic price effect in Spain decreased to €1.7 per MWh for each additional GWh of wind energy, while it increased across the border. The impact of Spanish wind energy on reducing French electricity prices became more pronounced, with each additional GWh of wind generation in Spain reducing French prices by €0.27 per MWh, i.e. 0.8 percent of the average price.

Then, I calculate the cost per ton of CO_2 avoided through the wind subsidy system in Spain, as well as the net cost borne by the Spanish consumer who pays for this subsidy. The cost slightly increased after the expansion, from 112 euros to 143 euros (whether in Spain or France). Additionally, taking into account the price effect in Spain, I find that the Spanish consumer benefited from a net gain of 26.1 euros per ton of CO_2 avoided pre-expansion, which decreased to 3.6 euros post-expansion.

Finally, the marginal impact of wind generation on welfare is computed. In addition to the impact on consumer surplus, I consider the profit loss of generators in both countries due to the price effect, and the gains related to the reduction of CO_2 emissions. I find that the break-even point at which subsidizing wind power in Spain becomes welfare improving occurs for a social cost of carbon of approximately €60/tCO_2 pre-expansion and €70/tCO_2 post-expansion.

These results are robust to a variety of specifications, including controlling for wind generation in neighbouring Germany, varied temporal fixed effects and the use of a global polynomial approach or alternatively a local linear approach.

To the best of my knowledge, this paper provides the first estimate of the impact of increased electricity interconnection between two countries with thermal polluting generation on the value of renewable energy. Previous literature has examined how renewable electricity reduces CO_2 emissions by displacing thermal generation (Cullen, 2013; Fell and Linn, 2013; Kaffine et al., 2013; Novan, 2015; Holladay and LaRiviere, 2017; Callaway et al., 2018; Sexton et al., 2018; Abrell et al., 2019; Gugler et al., 2021; Petersen et al., 2022) and impact market prices (Prol et al., 2020; Bushnell and Novan, 2021; Abrell and Kosch, 2022; Peña et al., 2022; Petersen et al., 2022) in a given market. For the papers on the the environmental value of renewable energy, they all find that renewable electricity offsets CO_2 emissions, and that this effect varies depending on the structure of the electricity mix. The issue of emissions offset in connected countries has not been empirically addressed, except by Abrell and Kosch (2022). They demonstrated that the promotion of renewable energy in Germany effectively reduces emissions in neighboring countries. As for the papers on the impact of renewable energy on electricity prices, they have garnered interest for a more extended period than those focused on the effects on emissions. This phenomenon is commonly referred to as the 'merit order effect'. It has been widely demonstrated that electricity market prices in a given market area decrease with the increase in renewable generation.

This effect on prices in interconnected importing countries is also of interest. It is likely that these prices too are influenced downward, as lower local prices due to the domestic merit order effect stimulate exports. This intuition has been empirically verified by Phan and Roques (2015), Grossi et al. (2018) and Abrell and Kosch (2022) for the case of Germany and its neighboring countries. An important point is that this anticipated price decrease is enabled by renewable energy support programs funded by consumers in the country of origin of the electricity. The question of who benefits from the policies funded in a specific country thus arises. Moreover, a negative effect for producers in neighboring countries is the reduction in their profits due to the contamination of their market prices. In this case study, I aim to quantify these effects and investigate whether they have been modified by the available interconnection capacity.

Other studies have examined theoretically the role of transmission expansion on wholesale electricity markets (Borenstein et al., 1999; Joskow and Tirole, 2000, 2005). A more recent segment of the literature, to which our study is closely related, has focused on the ex-post evaluation of the consequences of expanding interconnections between regions abundant in renewable resources and demand centers with carbon-intensive production (Fell et al., 2021; Gonzales et al., 2022). The former has found that relaxing transmission constraints between these two types of regions increases the environmental value of renewables by displacing carbon-intensive generation. The latter has found that market integration leads to price convergence between two regions, an increase in renewable generation, and a reduction in emissions. I differ from these studies in several respects. I examine the expansion of interconnection capacity between two countries rather than within a single country among different regions. Therefore, the issues related to cost allocation and emissions reduction are distinct. Each country has its own climate pledge and makes decisions regarding investments in renewables independently. Furthermore, France and Spain consistently have thermal generation at the margin with coal or gas. Hence, I am not studying the connection of a region with nearly entirely decarbonized generation with a region with polluting production. Instead, I investigate the interconnection of two regions, each with both zero-carbon and carbon-intensive assets and different price structures. Improved integration results in the ability to exchange more electricity but also relocates generation to the country with the lowest cost. However, the level of pollution from a power plant is not necessarily correlated with its marginal cost. Therefore, while must take wind energy offsets the costlier generation between two zones when there is no congestion, its effect on emissions can be suboptimal. For instance, it may lead to the avoidance of more expensive but less polluting gas generation rather than coal generation. Additionally, there could be an incentive for one country to freeride on the renewable energy subsidy policies of neighboring countries, while on the other hand, there might be a decrease in the effectiveness of domestic subsidies that are intended to achieve national climate targets. I take advantage of my unique setup to investigate this hypothesis.

This paper holds implications that extend beyond the specific case of France and Spain, with broader relevance to energy policy and the transition to renewable energy sources. By analyzing the effects of interconnection on CO_2 emissions and electricity prices, this research contributes to the understanding of the potential benefits and challenges associated with cross-border cooperation and market integration in achieving environmental and economic objectives. Furthermore, it sheds light on the dynamics between renewable energy deployment, market interconnections, and the effective reduction of greenhouse gas emissions.

The rest of the paper is organized as follows. Section 2 provides background on European policy promoting electricity market integration and presents a simple conceptual framework. Section 3 describes our data. Section 4 outlines our identification strategies and results. Section 5 presents the welfare approach. Section 6 discusses the results and their implications. Section 7 concludes.

2 Background and Conceptual Framework

This section provides background and clarifications on the main concepts addressed in this paper. It begins by documenting the commonly expected benefits associated with the integration of electricity markets. Then it reviews the literature on the environmental value of renewables and the merit order effect. Following this, it describes the Spanish wind energy subsidy system. Finally, it develops a simple conceptual model to offer insight into the anticipated effects and their potential ambiguity.

2.1 Benefits of electricity markets integration

Establishing a well-integrated European electricity market is a key objective for promoting the energy transition, integrating renewable energy sources, enhancing energy security, and reducing wholesale prices. This involves a process of pooling electricity supply and demand across different price zones, thereby enabling an overall maximization of the economic value of these zones. When the interconnection capacities between two price zones are not congested, meaning that the power flowing through the interconnections is less than their physical capacity, market coupling involves price convergence between these zones. An algorithm simultaneously determines prices and implicitly allocates cross-border capacities. If the interconnection capacity allows, the country with the least expensive generation exports while the one with the costlier generation imports until price parity is achieved. However, if the capacity between the two zones is insufficient, price convergence is not guaranteed.

Since mid 2014, which is before the start of our study, the interconnection capacity between France and Spain has been implicitly allocated. This means that it is jointly allocated with energy exchanges. In practice, for spot markets, market participants in each zone submit their daily buy and sell order books to their Nominated Electricity Market Operator (NEMO) before noon. The Transmission System Operators (TSOs) provide information about exchange capacities at the borders and allocation constraints to the Regional Coordination Centers, which calculate cross-border exchange capacities for each region. The NEMOs then execute the EUPHEMIA algorithm, which calculates prices and simultaneously allocates cross-border capacities across all of Europe, maximizing the total economic value. The capacity of cross-border electricity interconnections is a limiting factor for full market integration, meaning constant verification of the "Law of One Price". Therefore, the EU has set a target for member countries to achieve 15% interconnection of their annual production by 2030 (Commission, 2017).

The integration of electricity markets through the development of new electric interconnection capacities is strongly promoted at the European level. As an example, a communication from the European Commission in March 2023 states: "To achieve its climate and energy goals, Europe needs to improve cross-border electricity interconnections. Connecting Europe's electricity systems will allow the EU to boost its security of electricity supply and to integrate more renewables into energy markets", and "An integrated EU energy market is the most cost-effective way to ensure secure, sustainable, and affordable energy supplies to EU citizens. Through common energy market rules and cross-border infrastructure, energy can be produced in one EU country and delivered to consumers in another". The arguments for promoting integration which are of interest in this paper are those related to achieving climate goals through facilitating the deployment of renewable energies. The intuition for deploying more renewables stems from the argument that increased exchange possibilities between zones would lead to harnessing reductions in the temporal fluctuation of distant sources. Specifically, additional transmission capacity would facilitate the diffusion of renewable energy when the wind blows or the sun shines. There would also be a reciprocal impact: a region with abundant renewable capacity could access cost-effective thermal generation from another zone on windless or sunless days. This is particularly pertinent for our case study, as Spain is one of the leading countries in Europe in terms of wind power capacity. Indeed, with 23 GW of capacity, Spain ranks as the fifth-largest producer worldwide and the second in Europe, trailing only behind Germany.

While these policies are vigorously advocated at the European level, the reception at the national level is more nuanced. The increase in interconnection capacity between France and Spain from 1400 MW to 2800 MW in 2015 involved an investment of approximately 700 million euros. Moreover, it is projected to reach 5000 MW in 2026 through the European Biscay Gulf project, estimated to cost 2850 million euros, with substantial European support of 578 million euros (CRE, 2023)[1]. However, disagreements emerged between the two nations regarding this project. According to a Reuters article [2], negotiations on the distribution of construction costs for the interconnection took place. Initially, France, being a predominant exporter to Spain, saw Spain agree to bear some of the French side's costs. This decision was influenced by Spain's anticipation of a decrease in its wholesale electricity prices by importing French electricity. Additionally, Spain likely views this project as essential to integrate its heavily invested renewable energy into a broader European grid. Notably, climate considerations are not central in this discourse. But the increasing Spanish wind power capacity and the challenges in the French nuclear sector have reshaped the dynamics. France now has less to gain from selling electricity to a region whose prices have converged towards its own, resulting in a narrower price spread. Conversely, Spain's expectation of significant price reductions is less likely. The key takeaway is that while the European Commission's

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[1] https://www.cre.fr/actualites/la-cre-et-la-cnmc-parviennent-a-un-accord-sur-la-repartition-du-financement-du-projet-d-interconnexion-electrique-entre-la-france-et-l-espagne-com, last access on the 05/03/2024

[2] https://www.reuters.com/business/energy/breakthrough-close-france-spain-undersea-electricity-link-sources-2023-03-02/, last access on the 05/01/2024.

arguments highlight communal European benefits from greater integration, national political debates reveal an awareness of potential winners and losers at the national level. The cost-benefit analysis of these projects is highly dependent on the contexts of national electricity markets. This paper contributes to the discourse on the distribution of environmental costs and benefits of market integration for consumers and producers in both countries.

These contemporary political considerations resonate in the economic literature. Empirical papers have extensively studied the impact of trade in general on the environment. Intuitively, two opposing effects are identified. The pollution haven hypothesis suggests that developing countries with low incomes become more polluted through international trade due to the relocation of polluting production activities to these countries. Given their generally less stringent environmental regulations and less advanced technologies, the net result on emissions could be negative. Conversely, the Factor Endowment Theory posits that capital-intensive polluting production activities will relocate to capital-abundant countries, namely wealthier nations. Empirical results vary depending on the environmental aspect and case studies, showing either positive or negative impacts of free trade on the environment. To cite a few seminal papers, starting with those finding a positive impact: Antweiler et al. (2001) demonstrated that for sulfur dioxide, a country's increased exposure to free international markets leads to a slight modification of its national pollution intensity while significantly increasing national production and income. This increase in production and income, leading to improved production techniques, results in a beneficial final effect on emissions: opening to international markets with a 1 percent increase in production and income causes, on average, a 1 percent decrease in national emissions. Copeland and Taylor (2004) argue similarly, finding little evidence to support the pollution-haven hypothesis, at least not as a primary determinant in the evolution of emissions related to free trade. They thus advise against using protectionism to improve environmental quality. Alternatively, Managi et al. (2009), accounting for the endogeneity of trade and income – differentiating themselves from Antweiler and Copeland – measured a negative effect of trade on SO_2 and CO_2 emissions in non-OECD countries but a positive effect in OECD countries, supporting the pollution-haven hypothesis. Hence, the environmental impact of trade openness is both empirically well-documented and significant in the context of combating climate change and local pollution when making trade policy decisions. However, the part of this literature concerning electricity markets is still in its early stages.

Economic papers on electricity markets and trade have primarily focused on the aspect of competition enhancement. The literature has highlighted the positive effects of market integration through enhanced interconnection capacity on competition. Theoretical papers have shown that if the interconnection capacity between two price zones is insufficient, large players can strategically congest transmission lines within their dominant zone. This phenomenon can be mitigated by relatively low-cost investments, considering the substantial benefits associated with improved competition (Borenstein et al., 1999, 2000). This has been empirically validated by Wolak (2015) and Ryan (2021). Using data from Alberta's electricity market, Wolak (2015) measured a net positive benefit on competition resulting from the expansion of transmission capacity, which led strategic suppliers to anticipate less congestion. Similarly, using data from India, Ryan (2021) assessed a 22 percent market surplus increase for the Indian electricity market with an expansion of transmission capacity.

Another segment of the literature focuses on the impact of increasing interconnection capacity on CO_2 emissions using simulation techniques. Early works by Denny et al. (2010) demonstrated that increasing interconnection between Ireland and Great Britain would lead to a reduction in CO_2 emissions in Ireland but an increase in Great Britain, resulting in no overall change in aggregate emissions. Similarly, Yang (2022) finds that establishing interconnections in line with the EU2030 target increases CO_2 emissions for the France-Spain and Germany-Poland pairs. From a methodological perspective, these papers provide significant insights but remain models that suffer from simplifications necessary for their resolution. Typically, they struggle to reflect the complexities of power system operations, particularly due to potential uneconomic dispatch or congestion constraints. They nonetheless challenge the argument that more interconnection is a means to achieving European climate objectives.

Analysis of the link between market integration and the environmental efficiency of renewables or the merit order effect are also scarce. The studies by Fell et al. (2021) and Gonzales et al. (2022) are the closest to my research in this regard. They conducted ex-post measurements of environmental benefits resulting from the expansion of transmission capacity between a region dominated by renewable energy and one dominated by thermal energy. They also measured greater price convergence. My study differs in several ways. While Fell focused on Texas and Gonzales on Chile, examining market integration within a single country, my research investigates market integration between two distinct countries - France and Spain. This cross-border aspect introduces distributive questions regarding renewable energy subsidies, which are addressed in my work. Additionally, both Fell and Gonzales study the expansion of transmission capacity between a 'clean' zone with predominantly renewable generation and a 'dirty' zone with polluting thermal generation. In contrast, this study involves the expansion between two zones where thermal generation is marginal. Consequently, the outcomes in my case may not align with their findings, underscoring the importance of this research in understanding the nuanced effects of market integration.

2.2 The environmental value of renewable electricity

As described above, the literature on the influence of market integration on the environmental value of renewable energies is still nascent. In contrast, substantial research exists on their environmental value within isolated markets. As summarized in Table A2 in annexes, there is a consensus that emissions savings are notable and vary depending on regional energy mixes and time-specific factors. Generally, studies indicate that 0.4 to 0.9 tonnes of CO_2 are avoided for each additional MWh of wind or solar power, consistent with the offset of emissions from natural gas or coal plants. The primary motive for promoting renewable energies centers on reducing emissions from conventional electricity generation. This consideration becomes pivotal in policy-making, particularly when deciding on subsidies for specific technologies in given areas. It is crucial to consider how many tonnes of CO_2 will be avoided and, ultimately, to determine the cost per tonne of CO_2 avoided. This is necessary as it allows for a comparative analysis of the efficiency of various clean technologies in various possible locations.

The two papers most closely related to mine are Abrell et al. (2019) and Petersen et al. (2022). They both focus on the case of Spain. Abrell et al. (2019) find a marginal abatement effect of wind in Spain between 0.250 and 0.786 tCO_2/MWh. They do not directly account for the emissions actually abated in France by Spanish wind power, but make assumptions about this effect. The value of 0.250 tCO_2/MWh is found considering only domestic abatement. Assuming that 100 percent of Spanish exports avoid coal generation, they find an average marginal CO_2 abatement effect of 0.786 tCO_2/MWh, their upper bound. Assuming that exports avoid gas generation, they find 0.463 tCO_2/MWh. Therefore, the true value would be between these two. While these results are interesting, they do not directly account for the impact on the French mix. Petersen et al. (2022) also find a marginal impact of an additional MWh of wind energy on emissions to be about 0.500 tCO_2, twice as high as Abrell's finding. The reason could be the study period: 2014-2015 for Abrell et al. (2019) versus 2008-2019 for Petersen et al. (2022). Two hypotheses to explain this: predominantly offsetting hydro during Abrell's study period, or a change in the carbon intensity of the marginal plant between the two periods, possibly driven by the end of Petersen's study period. Regardless, Petersen et al. (2022), not accounting for exports, also find that the marginal abatement effect at high levels of wind penetration is only 66 percent of its value at low levels of penetration. Their hypotheses for this are either a lower substitution of coal or wind curtailment. They add that they do not quantify the emissions avoided abroad through exports, which could compensate for the value they find at high levels of penetration. Notably, both studies have limitations in directly accounting for the cross-border environmental impacts. My research aims to build on these findings, exploring the cross-border environmental impacts of renewable energy between France and Spain. Intuitively, and in line with Petersen's argument regarding the potential offsetting of marginal abatement at high levels of wind generation, I anticipate that Spanish wind power not only facilitates emissions reduction within Spain but also contributes to lowering emissions in France by fostering exportation. I formalize this intuition in section 2.5.

2.3 Merit order effect

In order to fully address the distributive aspects, especially in cases where a subsidy in one country might have effects in another, it is essential to consider the price effect of wind generation. Renewable energies are known to exert a deflationary influence on wholesale electricity prices. Table A2 in the annexes offers a non-exhaustive review of the literature measuring this effect. Similar to the environmental value, most studies focus on the merit order effect within a single market. The extent of the effect is contingent on the steepness of the supply curve; the steeper it is, the more significant the expected impact. Abrell et al. (2019) and Petersen et al. (2022) also assess the merit order effect in Spain, finding an average impact of around -2 €/MWh for each additional GWh of wind generation. Intuitively, I anticipate that this merit order effect may also influence prices in France, underscoring the potential for significant cross-border economic impacts of renewable energy policies.

2.4 Wind power promotion in Spain

The massive deployment of renewable energies is a necessity to limit global warming to below 1.5°C. All models that maintain temperatures within the 1.5-2°C threshold involve a rapid decrease in emissions from fossil fuel energy production and a substitution with renewable energy (Intergovernmental Panel On Climate Change (Ipcc), 2023). Recognizing this challenge, the European Commission passed the revised Renewable Energy Directive in 2023, setting a target of 42.5% renewable energy in the EU mix by 2050 for climate neutrality – essentially doubling the proportion of renewable energy. During my study period of 2014-2016, this directive was not yet in effect. But the ambition, starting from 2001 with the Energy 2020 strategy, was already to reach 20% renewable energy by 2020[3].

In this context, Spain has been a European leader in experimenting with a succession of support mechanisms. The initial generation-based subsidy mechanisms like Feed-in-Premiums and Feed-in-Tariffs were discontinued and replaced in June 2014. Prior to my study, the Spanish government introduced a capacity-based remuneration mechanism, retroactively applied to all facilities that had not yet recovered their investment costs, mainly those installed after 2004 (Petersen et al., 2022). Consequently, during this period, the net financial support for wind power, which is of particular interest to us, was 64.60 € per MWh of wind output (Abrell et al., 2019) [4].

The goal being CO_2 emission abatement, it is crucial to determine the cost to the Spanish taxpayer per tonne of CO_2 avoided. The location of this tonne, whether in France or Spain, bears relevance. However, caution must be exercised in discussing this aspect. Each EU

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[3] Additionally, member countries had to report their progress biennially to the Commission.

[4] https://www.cnmc.es/estadistica/informacion-mensual-de-estadisticas-sobre-las-ventas-de-renovables-cogeneracion-y-46 for the data

member state has its own pledges for emission reduction. If one country reduces its emissions due to a public policy financed by another country, the question of which country should claim this reduction arises. Typically, observing that the country reducing emissions thanks to foreign investment reports the abatement as part of its pledge would highlight the incentive to freeride on the renewable energy subsidy policies of a more enterprising neighboring country.

However, in terms of emission levels, this debate holds limited significance for two reasons. First, CO_2 is a global pollutant. Regardless of where it is emitted or avoided, the final effect on atmospheric concentration remains the same. Secondly, electricity production is covered by the EU Emissions Trading System. Hence, supplementary policies like renewable subsidies represent an overlapping climate policy that affects who emits but not the aggregate emissions. This is known as the waterbed effect[5]. Therefore, while assessing the change in the environmental value of wind energy with market integration may seem less pertinent, evaluating the impact on consumer surplus and the program costs of carbon abatement remains critical. The underlying question is who pays and who benefits. Who pays is clear in the context of this study. Who benefits must be measured.

2.5 Conceptual Framework

This section provides insight into how an increase in transmission capacity can impact the effect of renewable generation on prices and emissions. I expand upon the model used by Joskow and Tirole (2005), and Fell and Kaffine (2018) to consider two regions with thermal capacity, one of which includes renewables, and a negative externality represented by CO_2 emissions. By employing this model, I illustrate the potential variations in the marginal CO_2 abatement effect of wind energy and its influence on prices based on various fuel price scenarios, the CO_2 price, the capacities of different technologies in each region, and the level of transmission capacity between the regions. I consider two possible scenarios: ”congested” when the interconnection is constrained and ”uncongested” when it is not. I consider a highly simplified model for illustration purposes, which will help us gain insight into the ambiguity of expected results. Let us consider Spain as a country rich in wind power capacity, producing W units of wind energy at zero marginal cost. Spain also has thermal generation F_s, composed of coal and gas power plants. $M_c(F_s)$ is the marginal cost of the marginal thermal plant. I will simplify further by assuming that France has nuclear and thermal generation F_f, with the marginal cost of the marginal power plant being $M_c(F_f)$. Let us recall that the cost of the marginal power plant corresponds to the market price. The electricity demands of both countries are considered fixed, with values L_f and L_s. Finally, let us assume that in autarky (self-sufficiency), the marginal Spanish power plant is cheaper than the French one. I will relax this hypothesis later.

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[5] See Perino (2018) and Rosendahl (2019) for some considerations on the EU ETS waterbed effect.

Therefore, I focus on the hours when Spain is exporting to France. Both countries can exchange a volume Q with $\mid Q \mid \leq K$, where K represents the transmission constraint. Thus, $F_s = L_s - W + Q$ and $F_f = L_f - Q$. Assuming prefect competition, the uncongested regime verifies:

$$MC_s(L_s - W + Q) = MC_f(L_e - Q) \tag{1}$$

A first observation is that compared to the case of autarky where Q = 0, the price in Spain has increased, and the price in France has decreased until they are equal. From equation 1, I deduce that an exogenous marginal increase in wind generation alters the exchanges between the two countries and their respective thermal generations by the following quantities:

$$\frac{dQ}{dW} = \frac{MC'_s}{MC'_f + MC'_s}; \frac{dF_s}{dW} = -\frac{MC'_f}{MC'_f + MC'_s}; \frac{dF_f}{dW} = -\frac{MC'_s}{MC'_f + MC'_s} \tag{2}$$

Therefore, a marginal increase in Spanish wind generation leads to an increase in the flow from Spain to France and a decrease in thermal generation in both countries, according to the relative slopes of the country marginal cost curves. Market prices and emissions related to thermal generation decrease in both countries with this marginal increase in wind power. On the other hand, if the interconnection is congested with Q = K, the prices in the two countries differ:

$$MC_s(L_s - W + K) + \eta(K) = MC_f(L_e - K) \tag{3}$$

where $\eta(K) > 0$ is the shadow cost of the transmission constraint. The effects of a marginal increase in wind generation is now:

$$\frac{dQ}{dRE} = 0; \frac{dF_s}{dRE} = -1; \frac{dF_f}{dRE} = 0 \tag{4}$$

So, with a congestion constraint, the additional wind generation offsets thermal generation in Spain only and reduces prices there only. The question I am then asking is as follows: in which scenario is the environmental value of renewables and the price reduction due to them the greatest? For the emission effect, it will depend on the carbon intensity of the marginal power plants in each country and in each regime. Depending on the relative prices of coal and gas, the price of CO_2, and the demands of the two countries, two cases are possible. The first case with a marginal gas power plant in both Spain and France, and the second case with a marginal coal power plant in Spain and a marginal gas power plant in France. For the first case, assuming that the carbon intensity of gas power plants in both countries is the same, the emissions avoided by an additional unit of wind power would be the same for both the congested and uncongested regimes. As for the price effect, the reduction in the average price depends on the relative slopes of the two supply curves. In other words, the effect of transitioning from one regime to another can be positive or negative in terms of the price effect of renewables. For the second case, an additional unit of wind power would reduce coal generation in Spain by the same amount, while in the uncongested case, the reduction in thermal generation due to the additional wind unit would be shared between gas generation in France and coal generation in Spain. Given that coal emit twice as much CO_2 as gas on average, the environmental value of wind power would be higher in the congested regime. The reasoning for the price effect is the same as in the first case: it depends on the relative slopes of the supply curves. Increasing interconnection capacity effectively reduces the probability of a given hour being in the ”congested” regime. As the simple model above provides insight, the impact of such a policy on the value of renewables is ambiguous. Therefore, I aim to quantify these effects in the case of the capacity increase between France and Spain in 2015. Furthermore, the electrical system is complex, and modeling emissions reduction ex ante, especially due to non-economic dispatch, would be challenging. Hence, using real-world data in this case is necessary.

3 Data

I collect hourly data from the French and Spanish electricity markets, covering a period of one year before and one year after October 2015, which marks the availability of additional interconnection capacity. This means that the dataset consists of roughly 17,500 observations. The analyzed time period is rather short in order to minimize the risk of also capturing market adjustments caused by the interconnector expansion, e.g. investments in new power plants. The generation data for Spain and France are sourced from their respective transmission system operators, REE and RTE. Prices for coal, natural gas, and the EU ETS (Emissions Trading System) are obtained from Bloomberg. Prices for natural gas and for CO_2 are at the daily level whereas prices for coal are at the monthly level. Hourly temperature data is from the European Climate Assessment and Dataset website, while the production index is constructed by the OECD. I calculate the coal over gas cost ratio by taking into account the CO_2 price.

3.1 Electricity mix in Spain and in France

This subsection presents the composition of the French and Spanish electricity mixes. The two countries differ in their installed capacities as indicated in Table 1.

The first observation is that the installed capacity by technology type remained stable over the studied period. Thus, I argue that potential construction or decommissioning of production assets does not influence my results. The details of the plant portfolios of the two countries, starting with Spain, are the following. In order of magnitude, the largest

Table 1: Installed capacity (MW)

	Spain		France	
	Before expansion	After expansion	Before expansion	After expansion
Natural Gas	28,268	28,268	6,121	6,121
Coal	10,962	10,030	4,810	2,930
Nuclear	7,573	7,573	63,130	63,130
Hydro	17,043	17,050	10,314	10,325
Pumped storage	3,331	3,331	4,965	4,965
Wind	22,920	22,971	10,322	11,761
Solar	4,684	4,689	6,191	6,772
Total capacity	105,657	104,557	121,039	121,350

Note: Data are taken from REE for Spain and from RTE for France. "Before expansion" is the 12 months average installed capacity before October 2015, "After expansion" the 12 months average value after October 2015.

share of installed capacity in Spain is gas plants, representing 26 percent. The country is characterized by a significant portion of its total capacity coming from wind at 22 percent. Next are hydro and coal with 16 and 10 percent, respectively. Solar represents 4 percent of the total capacity. Table 4 provides the annual generation values before and after the increase in transmission capacity for both countries. Due to the heterogeneity of load factors, the order of importance of technologies changes. The most significant portion of production comes from nuclear and coal plants used for base-load, with average load factors of 81 and 53 percent, respectively. Then comes wind, and finally natural gas, which is used for peak-load with a very low load factor of 12 percent. This underlines the overcapacity of gas plants in Spain over this period. For Spanish wind and solar, the important observation is that generation is almost the same in both periods, which means, apart from possible

Table 2: Annual generation (TWh)

	Spain		France	
	Before expansion	After expansion	Before expansion	After expansion
Natural Gas	32	32	14	22
Coal	52	47	8	8
Nuclear	54	56	415	416
Hydro	28	36	68	59
Pumped storage	2	3	-	-
Wind	48	48	17	21
Solar	8	8	5	7
Total consumption	267	261	540	546

Note: Data are taken from REE for Spain and from RTE for France. 12 months total generation by technology before and after October 2015.

curtailments, that the weather conditions are similar across both periods. I now turn to the case of France. Its mix is dominated by nuclear power, which is far ahead in installed capacity, accounting for 52 percent of the country's total capacity and 76 percent of total generation. During the period studied, no major maintenance issues significantly impacting the availability of these plants were reported. In terms of capacity, hydro, wind, solar, gas, and finally coal follow in order. Of course, due to the intermittency of renewables, the order of importance in generation is again different. Thermal generation is used on the margin in France for about 5 percent of total generation. But these only 5 percent are responsible for almost all of the emissions from the French mix, with about 25 Mt annually over the period[6]. Biomass and fuel used as backup are responsible for a negligible part of these emissions. For scale, these 25 Mt represent one-twentieth of the country's total emissions. Although both countries have different energy mixes, they share the common feature of resorting to polluting fossil fuels at least marginally, be it natural gas or coal.

Connecting these two countries, therefore, differs from the cases studied by Fell et al. (2021) and Gonzales et al. (2022). In contrast to these papers, which assess the impact of connecting a "clean" zone dominated by zero-emission renewable energies with a "dirty" zone dominated by polluting thermal power, the France-Spain case is indeed one where two "dirty" zones are connected as shown by the descriptive statistics. Admittedly, the carbon intensity of the French electricity mix is relatively low, but it is the marginal carbon intensity, typically from coal or gas, that matters when it comes to quantifying the environmental value of renewable energy.

This analysis primarily focuses on the impact of Spanish wind energy for several key reasons. Firstly, the output from photovoltaic generation during the period in question is relatively low in both countries. Secondly, the solar generation exhibits minimal variation, being highly predictable and closely correlated with hourly seasonality. This aspect becomes particularly problematic given our control for demand, which shares a strong correlation with solar generation. Lastly, our analysis of photovoltaics is further constrained by the high correlation of solar generation between France and Spain (see figure A2 in annexes). These factors collectively render the task of distinctly identifying the impact of solar energy on prices and emissions in both countries quite complex. However, I argue that this limitation is mitigated by the relatively low level of solar generation during the period under study. Another argument pertains to the impact of each country's type of renewable electricity generation on cross-border trade. It is expected that volatile renewable energy generation leads to imports during periods of low generation and to exports when generation is high. To explore the impact of renewable generation on energy trade between France and Spain, I regress the exports on renewable generation, including demand and time-fixed effects to account for possible changes in available capacities by technology, and seasonal, daily, and

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[6] https://analysesetdonnees.rte-france.com/bilan-electrique-emission-ges

hourly cycles (see in appendix table A3). I find that Spanish solar power has a weak and non-significant effect on Spanish exports. French solar power also has non-significant low effect on exports from France to Spain. Finally, French wind power has a significantly positive marginal effect, but it is twice as weak as that of Spanish wind power. Given that total Spanish wind generation is two to three times higher than in France, this paper focuses solely on Spanish wind generation.

In the rest of the paper, I focus on the impact of volatile wind generation on carbon-based assets such as coal and gas plants. I exclude hydro generation from my analysis as it can dynamically influence my results and not contemporaneously. I leave these considerations for exploration in future work.

3.2 Emissions

Hourly CO_2 emissions by country are calculated by multiplying the generation by each fuel type with its emission coefficient. These coefficients are available for each year for both Spain and France (International Energy Agency, 2016). They are calculated using the IEA energy data and in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [7]. On average, emissions per MWh from electricity generation using coal are slightly higher in France than in Spain, with 1.187 tCO_2/MWh compared to 947 tCO_2/MWh. The opposite is true for natural gas, with an average of 313 tCO_2/MWh in France and 349 tCO_2/MWh in Spain.

3.3 Wind generation and load

Figure 1 illustrates the average hourly variations in electricity demand in both countries and wind generation in Spain. Figure A1 in the annex presents the average monthly variations, calculated as the monthly averages of hourly data. The initial observation is that both demand levels and wind generation exhibit substantial hourly variation. This suggests that the marginal impact of wind generation on thermal generation depends on the time of day. Typically, demand is lower at night and in the early morning in both countries. On a monthly horizon, it is lower in spring and autumn in Spain due to the use of air conditioning in the summer months, and in summer in France. If wind is generated during these times, it is the base-load generators with relatively low marginal costs that are more likely to be displaced. Conversely, during peak demand periods, wind energy is more likely to replace generators with relatively higher marginal costs. Another observation is that there is more wind generation in the afternoon and early night, as well as in winter, which corresponds to the demand peak in France. A key point for analysis using a discontinuity method is that

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[7] See: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

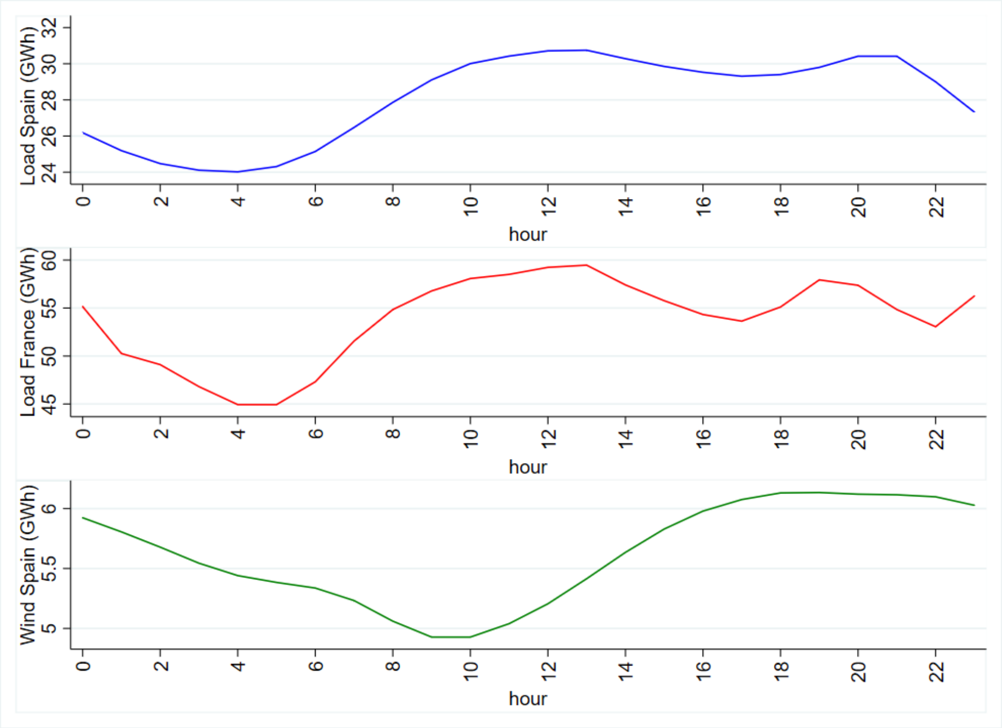


Figure 1: Average daily electricity demand in Spain and France and Wind generation in Spain (GWh)

wind generation did not change over time, as show Table 2. It remains the same pre and post expansion.

Comparing demand variations between the two countries, the most significant observation is the difference in spread between off-peak and peak demand months. Winter and summer demand in Spain is about 15 percent higher than in autumn and spring, which is relatively small. In contrast, in France, the difference between summer and winter is about 66 percent, due to the high winter demand for heating, which is predominantly electric.

3.4 Cost ratio

To account for potential changes in the merit order of generation units, I incorporate the coal-to-gas cost ratio into the analysis. I calculate this cost ratio as the ratio of the prices of each fuel in €/MWh of electricity produced, considering the CO_2 price. This involves multiplying the price of the EU ETS in €/tCO_2 by the emission coefficient of each type of fuel in tCO_2/MWh. On average, the coal-to-gas cost ratio is 0.36 pre-expansion and 0.52 post-expansion. Therefore, the marginal cost of coal is lower than that of natural gas during the sample period. This implies that coal plants are more likely to be dispatched before gas plants to meet the base-load. Consequently, one would expect a greater environmental value from an additional GWh of wind energy when demand is low, particularly in the case of Spain, which has a significant portion of its generation produced from coal as shown in section 3.1. It is noteworthy that there is a decoupling between marginal costs and emission factors. The most polluting plants are dispatched before the less polluting ones.

4 Empirical Analyses

This section is structured as follows. The identification strategy for both the CO_2 marginal abatement effect and the CO_2 cross-border marginal abatement effect is outlined. The results and their heterogeneity from this subsection are then presented and discussed. The same structure is subsequently applied to the merit order effect and the cross-border merit order effect. Finally, robustness tests are presented.

4.1 Marginal abatement effect and cross-border marginal abatement effect

4.1.1 Econometric framework

I use the method of Regression Discontinuity in Time (RDiT) as described by Hausman and Rapson (2017). Its advantage over a traditional event study lies in leveraging high-frequency data to incorporate flexible controls by utilizing higher-order time trend polynomials before and after the treatment. The concept underlying this approach is that the dependent variable, whether emissions or thermal generation in this context, would have changed smoothly around the treatment date in the absence of the treatment. Specifically, what I do is the following:

I start by regressing the dependent variables *emissions in Spain* (e_t^s) and *emissions in France* (e_t^f) on *wind generation in Spain* ($Wind_t^s$) with an indicator for observations after October 24th 2015, various control variables and a flexible n-th order polynomial time trend g(t):

$$\begin{aligned} e_t^s &= \alpha_0 1\{t \geq 10/2015\} + \alpha_1 Wind_t^s + \alpha_2 Wind_t^s \times 1\{t \geq 10/2015\} \\ &\quad + \sum_j \theta_{\mathbf{j}} f_j(\mathbf{X_t}) + \alpha_{\mathbf{3}} \mathbf{Cal_t} + g(t) + u_t \end{aligned} \tag{5}$$

$$\begin{aligned} e_t^f &= \beta_0 1\{t \geq 10/2015\} + \beta_1 Wind_t^s + \beta_2 Wind_t^s \times 1\{t \geq 10/2015\} \\ &\quad + \sum_j \kappa_{\mathbf{j}} f_j(\mathbf{X_t}) + \beta_{\mathbf{3}} \mathbf{Cal_t} + g(t) + u_t \end{aligned} \tag{6}$$

where e_t^{spain} and e_t^{france} are hourly CO_2 emissions in tons, $Wind_t^s$ is hourly wind generation in Spain in MWh, and $1\{t \geq 10/2015\}$ is an indicator that takes the value one if the observation corresponds to an hour after October 24th 2015 and is zero otherwise. X_t is a set of controls for load in France and in Spain (L_t^s and L_t^f), CR_t the coal over gas price ratio to control for changes in fuel cost and the wind generation in France $Wind_t^f$. All these controls are fully interacted with $1\{t \geq 10/2015\}$. Cal_t is a vector of calendar variables including hour of day, day of week and month-of-year fixed effects to control for possible changes in the generation mix as well as for the impact of seasonal and daily cycles. g(t) is a n-th order polynomial time trend. Our coefficients of interest for equation 5 are α_1, representing the CO$_2$ marginal abatement effect of spanish wind generation before the interconnection expansion, and α_2 representing its change after the expansion. For equation 6, β_1, represents the cross-border CO$_2$ marginal abatement effect of spanish wind generation on french emissions before the interconnection expansion, and β_2 representing its change after the expansion. The expected sign of α_1 and β_1 is negative as wind generation with zero marginal cost is expected to offset some polluting thermal plants in both countries. β_2 is also expected to be negative as more electricity is being sent from Spain to France after the interconnection capacity increase. The sign of α_2 is ambiguous. As detailed in Section 2.5, it could be positive under certain settings. I am specifically investigating by how much, due to exports to France when Spain produces a significant amount of wind energy, less Spanish thermal generation is offset as a result of increased interconnection between the two countries.

Then, to disentangle the effect of $Wind_t^s$ on each major polluting source of electricity i, I employ the hourly generation by fuel type in each country c as the dependent variable, which is regressed against its key determinants:

$$\begin{aligned} g_{i,t}^{c} &= \gamma_{0i}^{c} 1\{t \geq 10/2015\} + \gamma_{1i}^{c} Wind_t^s + \gamma_{2i}^{c} Wind_t^s \times 1\{t \geq 10/2015\} \\ &\quad + \sum_{j} \lambda_{\mathbf{ji}}^{\mathbf{c}} f_j(\mathbf{X_t}) + \gamma_{\mathbf{3i}}^{\mathbf{c}} \mathbf{Cal_t} + g(t) + u_{i,t} \end{aligned} \tag{7}$$

where $g_{i,t}^{country}$ is coal or gas generation in Spain or in France. The coefficients of interest in this regression are γ_{1i}^c and γ_{2i}^c and they capture the marginal effect of Spanish wind energy on different polluting electricity sources in both countries and its evolution post expansion. Following the same reasoning as for the previous regressions, the expected sign of γ_{1coal}^{spain}, γ_{1gas}^{spain}, γ_{1coal}^{france} and γ_{1gas}^{france} is negative, that of γ_{2coal}^{france}, γ_{2gas}^{france} is also negative, and those of γ_{2coal}^{spain} and γ_{2gas}^{spain} are ambiguous.

4.1.2 Results and discussion

The estimation results of equations 5 and 6 are presented in Table 3. Before the expansion of the interconnection, Spanish wind energy offset 0.573 tons of CO$_2$ per MWh in Spain and a negligible amount in France. The treatment effect is similar to those found by Abrell et al. (2019) and Petersen et al. (2022), as discussed in Section 2.2. After the interconnection expansion, the amount of CO_2 avoided in Spain per MWh of wind generation decreased by 0.175 tons of CO_2 per MWh and increased by 0.045 tons of CO_2 per MWh in France. In total, the marginal abatement effect of Spanish wind energy on CO_2 has decreased from 0.579 to 0.449 tCO_2/MWh. Therefore, for the same amount invested, it has become more expensive to avoid a ton of CO_2.

Table 3: Emissions regression results

Variable	Spanish emissions	French emissions
	(1)	(1)
Wind Spain	-0.573***	-0.006
	(0.030)	(0.002)
Wind Spain $\times 1\{t \geq 10/2015\}$	0.175***	-0.045**
	(0.033)	(0.019)
Wind France	-0.059	-0.164***
	(0.046)	(0.012)
Load Spain	0.425***	0.026***
	(0.017)	(0.009)
Load France	0.061***	0.121***
	(0.009)	(0.006)
Cost Ratio	-897.041***	-609.179***
	(101.017)	(204.564)
Hours of day FE	YES	YES
Day of week FE	YES	YES
Month of Year FE	YES	YES
Fully interacted	YES	YES
N	29,228	29,228
R-squared	0.850	0.807

Note: Results for equations 5 and 6. BIC-chosen global polynomial. Coefficients can be interpreted as tCO_2/MWh. Newey–West standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

To provide a rough estimate, I calculate the average annual effect and examine how it is impacted by the expansion of interconnection by multiplying the marginal effects with the annual averages of wind generation before and after the expansion. On average and per year, 0.34 $MtCO_2$ were avoided in France due to Spanish wind power before the expansion, and this increased to 2.06 $MtCO_2$ after the expansion. This represents 6 percent of the emissions from the electricity mix and is thus non-negligible. Regarding the domestic effect, I find that 25.35 $MtCO_2$ per year were avoided in Spain due to domestic wind power, which decreased to 20.15 $MtCO_2$ per year after the expansion. In total, the increase in avoided emissions in France does not offset the decrease in avoided emissions in Spain due to Spanish wind energy.

The increase in the cross-border abatement effect was expected, as the flows to France have doubled and congestion between the two countries has decreased due to the additional interconnection capacity. However, how can we explain the decrease in the amount of emissions abated in Spain through wind energy? This decrease can be attributed to the hours when Spain exports to France. During these hours, generation from the most expensive power plant in Spain is not reduced due to an increase in wind generation; instead, it is exported if the interconnection is not congested to offset generation in France. This raises the question of which electricity sources in Spain would have been offset in the case of autarky.

Table 4: Generation per fuel type regression results

Variable	Spanish generation		French generation	
	Gas	Coal	Gas	Coal
Wind Spain	-0.245***	-0.463***	-0.009	-0.003
	(0.018)	(0.032)	(0.010)	(0.002)
Wind Spain $\times 1\{t \geq 10/2015\}$	-0.030***	0.164***	-0.044***	-0.025*
	(0.003)	(0.035)	(0.017)	(0.015)
Wind France	-0.067	-0.026	-0.202***	-0.064***
	(0.042)	(0.017)	(0.017)	(0.009)
Load Spain	0.372***	0.261***	0.025**	0.014**
	(0.018)	(0.018)	(0.011)	(0.006)
Load France	0.064***	0.032***	0.137***	0.053***
	(0.010)	(0.009)	(0.007)	(0.004)
Cost Ratio	4947.951***	-4227.808***	114.929	-176.617
	(1047.109)	(1298.578)	(82.653)	(494.902)
Hour FE	YES	YES	YES	YES
Month of Year FE	YES	YES	YES	YES
Fully interacted	YES	YES	YES	YES
N	29,228	29,228	29,228	29,228
R-squared	0.850	0.884	0.857	0.807

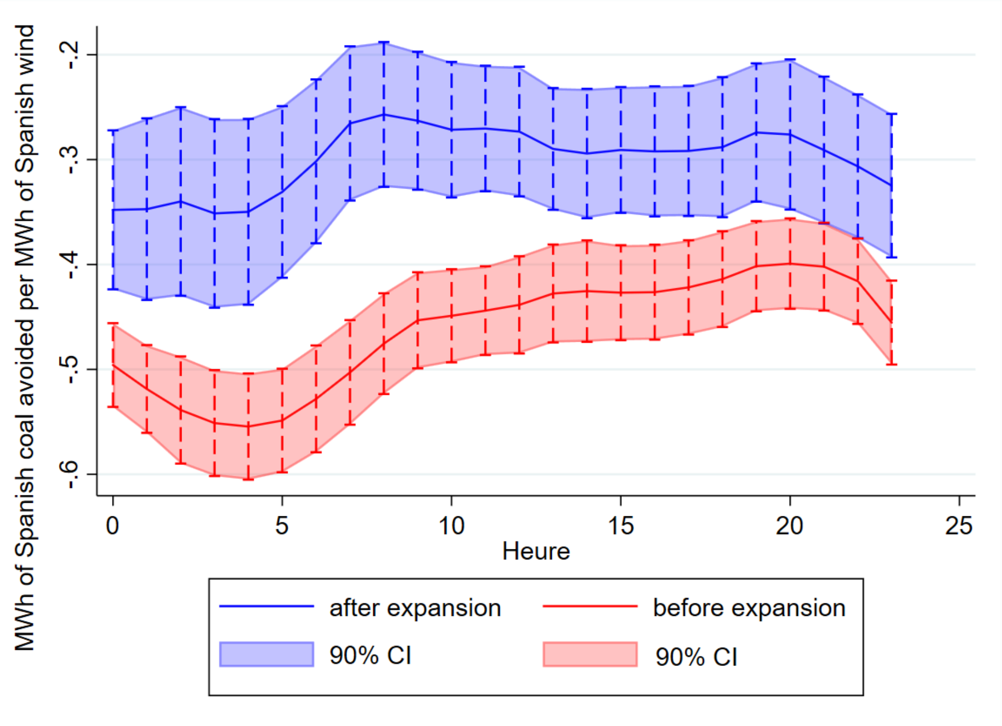
Note: Coefficients can be interpreted as MWh of thermal generation / MWh of wind generation. BIC-chosen global polynomial. Newey–West standard errors in parentheses. p<0.01, ** p<0.05, * p<0.1

In sum, the rise in market integration between France and Spain has caused a significant decrease in total CO_2 emissions abatement. I utilize the generation regressions to analyze this effect. Table 4 presents the results of regression 7. Examining the effect of Spanish wind energy on different types of generation shows that it displaces less domestic coal generation, which is the most polluting, after the interconnection expansion compared to before. Each MWh of Spanish wind energy displaces 0.164 less MWh of domestic coal and 0.030 more gas than before, explaining the negative effect on emissions reduction. One explanation is that coal is more frequently at the margin than gas when Spain exports to France. As for the generation displaced on the other side of the border, each MWh of Spanish wind energy displaces an additional 0.044 MWh of gas generation and 0.025 MWh of coal compared to before, which explains the increase in the cross-border CO_2 abatement effect. The findings suggest that the increase of the interconnection capacity leads to a greater reduction in gas generation compared to coal generation, which is unfavorable for the cumulative emissions of both regions. It should be noted that the magnitudes observed align with the findings documented in the literature, as discussed in Section 2.2.

4.1.3 Heterogeneous effects

As noted in section 3.1, the proportion of each type of generation varies throughout the day, and different conventional generators are marginal at different times. To delve deeper into the impact of the interconnection expansion on the environmental value of Spanish wind energy, I examine the hour-by-hour heterogeneity in the replacement of each type of technology. The replacement of coal in Spain and gas in France is particularly interesting, as the change in marginal CO_2 emissions primarily stems from these sources, as seen in section 4.1. Figure 2 plots the marginal impact of Spanish wind energy on coal generation in Spain hour by hour before and after the interconnection expansion.

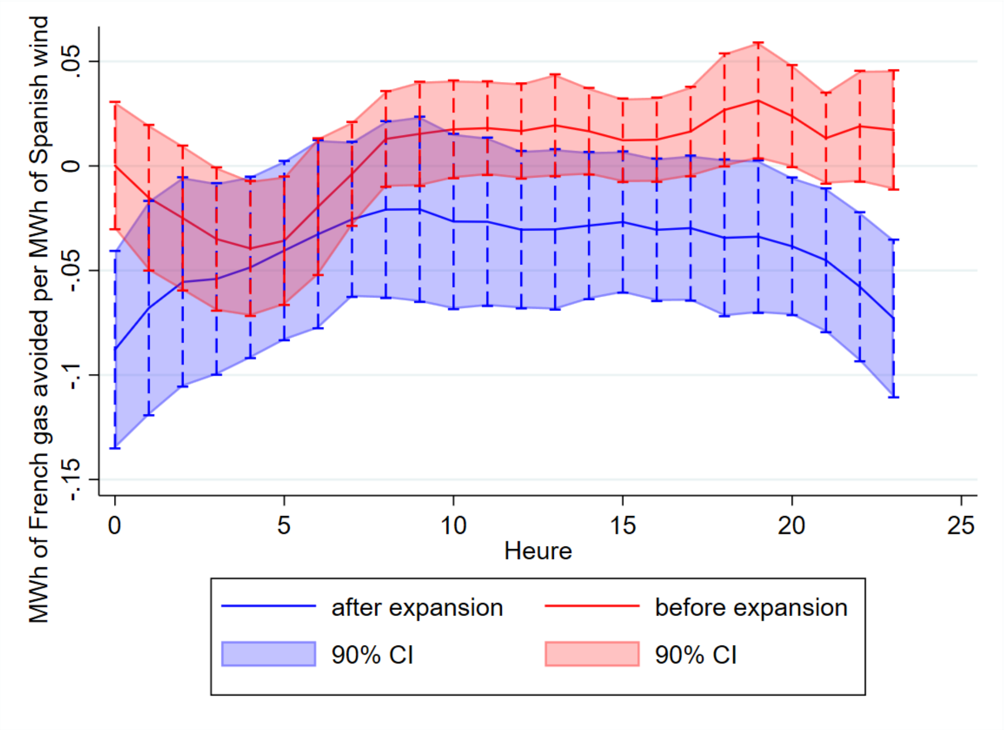
Figure 2: Hour-by-hour Spanish coal replacement per MWh of Spanish Wind Power



The initial observation is that the effect is not constant throughout the day. Consistent with existing literature (Kaffine et al., 2013; Novan, 2015; Fell and Kaffine, 2018), coal is predominantly displaced during low-demand hours. The coal displacement then decreases as domestic demand rises. Comparing this replacement before and after the expansion of the interconnection capacity shows that indeed less coal is displaced afterward. This change is mainly driven by low-demand hours at night, which is consistent with the period when coal, being cheaper than gas, is more likely to be marginal. The gap between the two curves then narrows during peak-load hours when gas is marginal.

Regarding gas generation displaced in France by Spanish wind energy, the effect also varies throughout the day. Figure 3 plots the replacement effect of gas generation in France by Spanish wind generation.

Figure 3: Hour-by-hour French gas replacement per MWh of Spanish Wind Power



Before the expansion, it is almost always insignificant. The observed minimum at night could be explained by the period when demand is low in both countries and wind generation is significant in Spain, triggering exports. However, the effect remains very weak. After the expansion, the analysis is less clear than for the domestic case, with coefficients not often significantly different from the pre-expansion case. Nevertheless, the inverted U-shape of the curve corresponds to the inverse of the average hourly wind generation curve displayed in Figure 1. It seems that the more wind generation there is in Spain, the more gas is displaced in France. This explanation should be taken cautiously, given the low significance of the hourly coefficients.

4.2 Merit order effect

4.2.1 Econometric framework

Last, I regress French and Spanish (country c) spot prices on the variable of interest $Wind_t^s$, along with a set of control variables that affect wholesale prices to investigate the cross-border merit order effect and its evolution with the interconnection:

$$\begin{aligned}p^c_t = \delta^c_0 1\{t \geq 10/2015\} + \delta^c_1 Wind^s_t + \delta^c_2 Wind^s_t \times 1\{t \geq 10/2015\} \\ + \sum_j \mu^{\mathbf{c}}_{\mathbf{j}} f_j(\mathbf{X_t}) + \delta^{\mathbf{c}}_{\mathbf{3}} \mathbf{Cal_t} + g(t) + u_t\end{aligned} \tag{8}$$

Here, X_t is slightly different compared to the previous equations. It is a set of controls for load in France and in Spain (L^s_t and L^f_t), p^{coal}_t the price of coal per MWh generated, p^{gas}_t the price of gas per MWh and p^{euets}_t the price of CO_2 per ton. Fuel prices are entered in level, unlike in previous regressions where the cost ratio was used. The reason is that the cost ratio was utilized to control for potential fuel switching. Here, it is indeed directly the price in level of the marginal plant that explains variations in electricity wholesale prices. One could argue that there is a risk of endogeneity of wind generation due to curtailment. As detailed in the background section, our study focuses on the period following the June 2014 regulation that introduced the capacity-based subsidy. Under this scheme, the incentive for wind generators to offer their production during periods of wind oversupply has logically been reduced.

Correctly identifying the impact of Spanish wind energy on prices in both countries requires accurate modeling of the supply curves. Our variable of interest is wind generation, but the potential endogeneity issue brought about by including demand as a control must be addressed. While electricity demand is often considered perfectly inelastic, the development of demand-side management tools raises concerns about demand reacting to price signals, leading to reverse causality. Therefore, I employ temperature, squared temperature, a national industrial production index, and hours of sunshine as instrumental variables. This results in the following first-stage regressions:

$$\begin{aligned}L^c_t = \rho^{\mathbf{c}}_{\mathbf{0}} \mathbf{Inst_t} + \rho^c_1 1\{t \geq 10/2015\} + \rho^c_2 Wind^s_t + \rho^c_3 Wind^s_t \times 1\{t \geq 10/2015\} \\ + \sum_j \rho_{\mathbf{j}}{}^c f_j(\mathbf{X_t}) + \rho^{\mathbf{c}}_{\mathbf{4}} \mathbf{Cal_t} + g(t) + u_t\end{aligned} \tag{9}$$

The Kleibergen-Paap Wald F-statistic always exceeds the weak identification (ID) critical values from Stock-Yogo which suggests that load is identified by the instruments.

As the shape of the supply curve is unknown and likely non-linear, I model it as flexibly as possible by estimating a semiparametric partially linear regression model with Robinson's (1988) double residual method. Consider a partially linear regression model of the type:

$$P_c = \theta_0 + \mathbf{Z_c}\theta + m(L_c) + \eta_c \tag{10}$$

where P_c represents spot prices in country c, $\mathbf{Z_c}$ is the row vector of control variables, and θ_0 is the intercept term. Variable L_c represents load and enters in a non-linear way according to a non-binding function m. η_i is the disturbance, assumed to have $E(\eta|L) = 0$. The double residual methodology applies conditional expectation on both sides leading to:

$$E(P_c|L_c) = \theta_0 + E(\mathbf{Z_c}|L_c)\theta + m(L_c) \tag{11}$$

And, through subtracting eq.10 from eq. 11, I get:

$$P_c - E(P_c|L_c) = (\mathbf{Z_c} - E(\mathbf{Z_c}|L_c))\theta + m(L_c) + \eta_c \tag{12}$$

where $P_c - E(P_c|L_c) = \eta_1 c$ and $Z_{kc} - E(Z_{kc}|L_c) = \eta_2 c$ reflect the residuals with k = 1,...,K indexing the control variables entering the model parametrically. In a two-step procedure I first obtain estimates of the conditional expectations $E_n(P_c|L_c)$ and $E_n(Z_c|L_c)$ from some non-parametric (kernel) estimations of the form $P_c = m_P(L_c) + \eta_{1c}$ and $Z_{kc} = m_{Z_k}(L_c) + \eta_{2c}$.

After inserting the estimated conditional expectations in eq. 12, I estimate the parameter vector θ consistently without explicitly modelling m(L$_i$) by a standard non-intercept ordinary least squares regression and I obtain $\hat{\theta} = (\hat{\eta_2'\eta_2})^{-1}(\hat{\eta_2'\eta_1})$. Finally, m(L) is estimated by regressing $(P - Z\hat{\theta})$ on L non-parametrically.

The endogenous nature of the non-parametrically modelled variable L, however, yields $E(\eta L) \neq 0$. As standard IV-techniques such as 2SLS and general method of moments (GMM) are not feasible in the context of endogenous variables that are non-linear in parameters, I apply a two-step residual inclusion control function and add the residuals ν fitted in the linear prediction of L in eq. 9 as control function to the semi-parametric regression model stated in eq. 11 (see Blundell and Powell (2004); Imbens and Wooldridge (2009)).

4.2.2 Results and discussion

The results of regression 8 are presented in Table 5. The domestic merit order effect decreased with the increase in interconnection, dropping from a reduction of 2.4 €/MWh per GWh of wind generation to 1.9 €/MWh per GWh.

By multiplying these values by the average hourly wind generation for each period, I determine that wind power reduced the average Spanish wholesale electricity price by 13 €/MWh before the expansion and 10 €/MWh after. Furthermore, the marginal effect of Spanish wind energy on French prices has increased after October 2015. By multiplying the marginal effect of Spanish wind energy on French prices by the average hourly wind generation for each period, I find that the spot price has decreased on average by a non significant 0.77€/MWh before October 2015 and by 1.72€/MWh after. For reference, the average wholesale prices were 39€/MWh in France and 50€/MWh in Spain before expansion, and 33€/MWh and 38€/MWh after. The deployment of Spanish wind energy has therefore led to a decrease in French prices, and this decrease has increased with the expansion of

Table 5: Merit order effect

Variable	Spanish prices	French prices
	(1)	(1)
Wind Spain	-0.00235***	-0.00012
	(0.00012)	(0.00023)
Wind Spain $\times 1\{t \geq 10/2015\}$	0.00052**	-0.00015***
	(0.00016)	(0.000024)
Wind France	-0.00005	-0.0015***
	(0.00014)	(0.000072)
Gas price	1.233***	2.248***
	(0.048)	(0.122)
Coal price	10.268***	2.075
	(1.314)	(3.284)
EU ETS	1.74***	-0.2
	(0.135)	(0.338)
Hours FE	YES	YES
Day of week FE	YES	YES
Month of Year FE	YES	YES
N	29,228	29,228
R-squared	0.810	0.815
F-test (1st stage)	78.092	71.561

Note: Results for equations 8. BIC-chosen global polynomial. Coefficients can be interpreted as €/MWh per MWh of wind generation. Newey–West standard errors in parentheses. p<0.01, ** p<0.05, * p<0.1

exchanges between the two countries. This result demonstrates that through its renewable energy subsidy system, Spain has lowered prices in France, which has also reduced the surplus of generators in France.

4.3 Robustness checks

I explore the robustness of my estimates under several alternative specifications. Initially, as an alternative to the polynomial approach, the local linear approach is tested with a rectangular kernel and a 30-day span in both the pre and post periods, adhering to the recommendations set forth by Hausman and Rapson (2017). The coefficients obtained Table A4 in the appendix are consistent with those from my primary specification, which I retain for subsequent robustness tests.

In the primary specification, all controls are interacted with the indicator variable for the expansion. I also estimate the regressions without this interaction, and the estimates closely align with those from my main specification as shown Table A5 in the appendix.

Maintaining the polynomial form of the Regression-Discontinuity-in-Time method, I experiment with different sets of temporal fixed effects. Load-hours fixed effects are employed to allow the impact of demand on emissions to vary by the time of day.

Lastly, the data are aggregated to the daily level to account for potential dynamic effects of wind generation. This adjustment considers the possibility that wind generation at time t might affect emissions at time t+n. Possible reasons include ramping or the use of hydro. If hydro is utilized to store electricity generated by wind, the emissions abated later when this stored energy is released can be attributed to wind energy, thereby contributing to its environmental value. The estimates under this specification are also consistent, as shown Table A6.

5 The cost of reducing CO_2 emissions

The previous analyses have shown that the environmental value of Spanish wind energy has decreased on an aggregate level with the increase in interconnection capacity, but it has increased for France. Since wind energy is subsidized with the aim of reducing CO_2 emissions, I compute the cost of abating one ton of CO_2 through wind energy. This is calculated by using a back-of-the-envelope approach. Net financial support is defined as the subsidy paid to renewable electricity producers minus the income received from selling their production on the market. This value, derived from CNMC (2018) data[8], was 64.60 euros per MWh over the period. The program's cost is then calculated as follows:

$$program\ \ cost = financial\ \ support/CO_2\ \ offset \tag{13}$$

I find a cost of wind promotion of 112 euros per ton of CO_2 avoided before the interconnection expansion and 143 euros after. This result is consistent with the literature, yet remains higher than the commonly accepted values of the social cost of carbon. However, this does not take into account the benefits of wind energy to those who finance it, namely the consumer, through the price effect. The subsequent question is how much does this cost the consumer? I assume that the wind subsidy is entirely paid by them. The price they pay to avoid CO_2 emissions thus corresponds to the price paid for each MWh of subsidized wind energy minus the merit order effect, relative to the amount of CO_2 emissions avoided. The back-of-the-envelope calculation is as follows:

$$consumer\ \ cost = (\Delta E)^{-1} \sum_t (F_e \times Wind^{spain} - \bar{D}_t \times |\Delta p^{spain}|) \tag{14}$$

With Δp the price effect, $F_e \times Wind^{spain}$ the net financial support for wind generation

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[8] https://www.cnmc.es/estadistica/informacion-mensual-de-estadisticas-sobre-las-ventas-de-renovables-cogeneracion-y-46

and ΔE the emissions offset.

The Spanish consumers were paying -26.1 euros per ton of CO_2 avoided before the expansion and -3.6 euros after. They benefit from a net gain as the decrease in electricity prices due to the merit order effect overcompensates for the increase due to subsidy payments. However, this gain has been reduced and is approaching zero. This is due to slightly lower price effect and wind generation over the year post-expansion. Nevertheless, the French consumer pays nothing and thus benefits for free from annually 2 mega tonnes of CO_2 abated after the expansion, which are financed at a rate of 143 euros per ton by the Spanish consumer post expansion.

6 Marginal impact of wind generation on welfare

The above section details the cost to the consumer, who ultimately finances the policy, of abating a ton of CO_2. While the price effect compensates for the subsidy cost, it impacts not only consumers but also producers. Recall that the day-ahead market operates with a uniform price auction. All called producers receive the price offered by the most expensive marginal plant times the quantity of electricity offered. Hence, wind power tends to decrease electricity producers' profits. Another impact of wind energy on surplus, not accounted for above, is the benefit from reduced CO_2 emissions. To incorporate these aspects for a more complete view of wind energy's effect on welfare, the results from Sections 4.1.2 and 4.2.2 are used to estimate the marginal impact of Spanish wind generation on economic welfare in France and Spain.

6.1 Decomposition of Economic Surplus:

Following the methodology proposed by Petersen et al. (2022) for surplus decomposition, I consider its breakdown in each country. The marginal impact of Spanish wind generation on surplus can be decomposed as follows:

$$\begin{aligned} \Delta EconomicSurplus = {} & \Delta ConsumerSurplus_{Spain} + \Delta ConsumerSurplus_{France} \\ & + \Delta ProducerSurplus_{Spain} + \Delta ProducerSurplus_{France} \\ & + \Delta EmissionsBenefits \end{aligned} \tag{15}$$

The change in consumer surplus differs between Spanish and French consumers as explained above. The Spanish consumer pays for the subsidy but benefits from the price effect, calculated as the change in market price multiplied by average demand. The French consumer benefits from the price effect but pays nothing in return. I calculate the change in consumer surplus for each country before and after the interconnection expansion.

The change in producers' surplus is the same on both sides of the border. It comprises two effects. The price effect refers to the change in rents for units whose output is not affected. They sell the same amount of energy but at a lower price. Additionally, the producer surplus is affected by the replacement effect, which corresponds to the foregone rents for units whose output is affected. For a marginal increase in wind generation, this equates to $\frac{\frac{\partial p}{\partial W}}{2}$.

Finally, the change in Emissions Benefits must be considered. Given that the Spanish electricity market is subject to the EU ETS, a portion of the emissions benefits is already accounted for. Therefore, I regress net emissions costs ($(SCC - p_{CO_2}) \times emissions$) using the same identification strategy as for equation 5. I directly calculate the change in the emission benefits of the two countries combined.

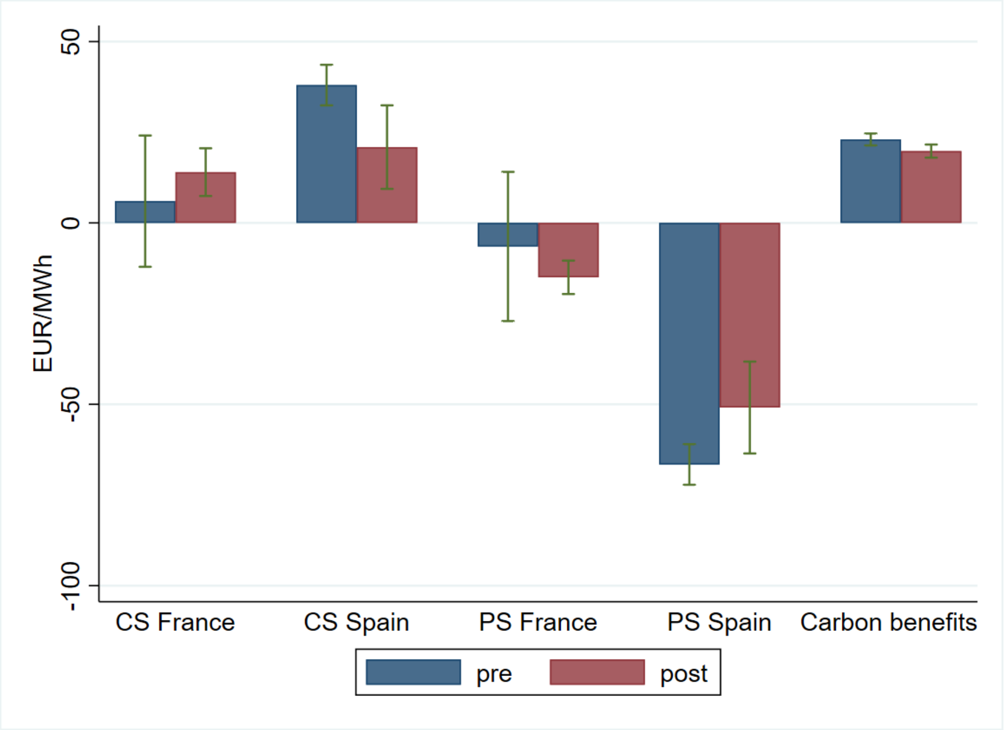
6.2 Results

Figure 4 presents the results of calculating the marginal impact of Spanish wind energy on economic surplus. As an illustrative example, the social cost of carbon chosen for calculating emission benefits is set at 50 €/tCO$_2$, a figure that will be varied in subsequent analyses. The focus here is to compare how the winners and losers of the wind subsidy are distributed between producers and consumers, as well as between countries. Pre-expansion, the impact of wind on the welfare of French consumers and electricity producers is not significant. In Spain, consumers gain and producers lose, resulting in a net lose without taking into account emission savings. Post-expansion, the gains for French consumers are offset by losses for French producers. This transfer due to marginal wind generation makes sense as French consumers do not pay the subsidy. In Spain, the gains for consumers and the losses for producers are both reduced.

To assess the complete effect on surplus, the reduction in emissions must be considered. This value depends on the social cost of carbon, which is highly debated. For instance, Nordhaus (2017) suggests recent estimates indicate damages of approximately \$30–100. At 50€/tCO$_2$, as shown in figure 4, the carbon benefits are insufficient to offset the producers' loss, making the marginal effect of wind on total surplus negative. Furthermore, the carbon benefits slightly decrease after the expansion of the interconnection.

Figure A3 in the annex plots the total effect on surplus from wind energy as a function of the social cost of carbon. The break-even point at which the policy becomes net beneficial is approximately 60€/tCO$_2$ before expansion and rises to around 70€/tCO$_2$ after. It should be noted that these two values of the social cost of carbon break-even points fall within the range recommended by climate scientists and economists. Still, the political implication of this result is that a social cost of carbon about 15 percent higher is required after the

Figure 4: Marginal Surplus Effects of Spanish Wind



Note: This figure shows the impacts of wind on consumer surplus (CS) and producer surplus (PS) in France and in Spain before and after the interconnection expansion as well as the impact on emission benefits with a SCC of 50€/tCO$_2$. Calculations based on marginal estimates from equations 5, 6 and 8.

expansion for marginal Spanish wind energy production to be welfare positive.

7 Policy discussion

The integration and harmonization of national electricity markets within Europe is a priority for the European Commission, something not questioned in this paper. However, member states retain significant latitude in decisions related to their national energy mixes and policies. The desire to maintain energy sovereignty is strong, and often leads to energy policy decisions being made unilaterally, without coordination with other member states. In the context of significant and increasing market integration, such unilateral national policies can impact interconnected markets. This is indeed what is found in this paper, aligning with the literature on market integration and unilateral policies. For instance, the increase in renewable capacity is the mirror's reflection of reduction in nuclear generation. While I find that Spanish wind energy has decreased French prices, enhancing consumer surplus and reducing profits for French generators, other papers, such as those studying the impact of nuclear plant closures in Germany following Fukushima (Grossi et al., 2017, 2018; Jarvis et al., 2019), typically show that phase-outs increased prices in connected countries, especially where interconnection capacity is high or number of congestion hours is low.

These examples present a real political challenge. The externalities of unilateral policy decisions by a member state imposed on others through market integration underscore the importance of coordinated European energy policy. While I do not propose that all strategic decisions should be centralized at the European Commission level, there is a clear need for more proactive monitoring and dialogue to assess national decisions' costs and implications. I add that this paper only considers short-term effects. Price changes contaminating connected countries can have longer-term effects, particularly impacting investment decisions. Various aspects of the economy are likely to be impacted and should be taken into consideration. From a macroeconomic perspective, a decrease in electricity prices increases the available income for consumers, which directly impacts real purchasing power and thus industrial production and GDP growth in both countries. Also, and specifically with respect to national power systems, a unilateral policy reform lowering prices in a neighboring country can create uncertainty about the construction of new power plants. Unilateral policy reforms can affect the future structure of the European energy mix and potentially create insecurity regarding the return on investment of new plants, potentially leading to under investment and consequent challenges to supply security. Thus, I advocate for the establishment of regulatory frameworks to ensure that decisions with significant cross-border impacts are subjected to comprehensive community-level discussions before implementation.

8 Conclusion

By using a Regression Discontinuity in Time design, I have found that the increase in interconnection capacity between France and Spain has decreased the domestic environmental value of Spanish wind energy, as it offsets less coal generation. However, it has increased this environmental value for France. Nevertheless, this increase does not compensate for the domestic decrease. This finding is important because it highlights that the impact of market integration on emissions is not necessarily positive, and the Franco-Spanish example is illustrative. These two countries have the particularity of relying on conventional generation on the margin. Market integration has the effect of relocating generation to where it is cheapest but not necessarily where it is the least polluting.

On the other hand, the well-known depressing effect of domestic renewable energy sources on prices contaminates foreign prices, and this effect becomes even more significant with increased exchange capacity. This is in line with what is found in the literature. In my back-of-the-envelope calculations, I find that the program cost of carbon abatement has slightly increased with the construction of the additional interconnection capacity, rising from 112 euros per ton to 143 euros. This cost is entirely borne by the Spanish consumer who, however, also benefits from the price effect. Once this effect is deducted, I find that the Spanish consumer gains: the merit order effect more than compensates for the cost of promoting wind energy. The gain has decreased, from 26.1 euros earned per ton of CO_2 avoided to 3.6 euros. In any case, the French consumer benefits for free from both the emission abatement due to Spanish wind generation, and from the price effect, which raises questions about the distributive stakes.

To determine whether subsidising wind power is beneficial for society in the short run, it is necessary to consider the expenses incurred for the renewable energy promotion program and assess the gain associated with the reduction in CO_2 emissions. Moreover, the impact on generator profits must be taken into consideration. Indeed, prices decrease in France, therefore the revenue of generators is affected as well. Simultaneously, I observe that domestic prices in Spain decreased less after the increase in interconnection, which can be beneficial for Spanish generators. There is a significant issue here regarding who bears the costs and who benefits. After accounting for changes in the profits of generators and gains related to CO_2 emissions reduction, the Spanish wind subsidy policy is welfare improving for a social cost of carbon of approximately €60/tCO_2 pre-expansion and €70/tCO_2 post-expansion.

This paper has implications that go beyond the case study of France and Spain. It suggests that a precise evaluation of the expected environmental and economic benefits related to the integration of European price zones should be conducted systematically. This should be the case, for example, for future increases in interconnection capacity between countries with varying degrees of polluting generation.

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A Appendices

A.1 Literature

Table A1: Emissions Offsets Due to Renewable Electricity

Paper	**Region**	**Emissions Offsets**
Cullen (2013)	Texas	0.430 tCO_2/MWh (wind)
Fell and Linn (2013)	Texas	0.512-0.514 tCO_2/MWh (wind) 0.745 tCO_2/MWh (solar)
Kaffine et al. (2013)	Texas	0.523 tCO_2/MWh (wind)
Graff Zivin et al. (2014)	WECC and Eastern interconnection (US)	0.370 tCO_2/MWh (solar, WECC) 0.555 tCO_2/MWh (solar, Eastern)
Novan (2015)	Texas	0.63 tCO_2/MWh (wind)
Holladay and LaRiviere (2017)	US regions	2044-5745 tCO_2/MW of installed wind capacity per year 1006-2131 tCO_2/MW of installed solar capacity per year
Callaway et al. (2018)	US regions	0.566-0.811 tCO_2/MWh (wind) 0.587-0.791 tCO_2/MWh (solar)
Abrell et al. (2019)	Germany and Spain	0.175-0.530 tCO_2/MWh (wind, Germany) 0.233-0.600 tCO_2/MWh (solar, Germany) 0.250-0.786 tCO_2/MWh (wind, Spain) 0.168-0.797 tCO_2/MWh (solar, Spain)
Gugler et al. (2021)	Germany and Great Britain	0.386 tCO_2/MWh (wind, Germany) 0.934 tCO_2/MWh (wind, GB)
Petersen et al. (2022)	Spain	0.500 tCO_2/MWh (wind, Spain)

Table A2: Merit order effect

Paper	**Region**	**Merit Order Effect**
Bode and Groscurth (2006)	Germany	0.55-0.61 €/MWh per additional 1GW of renewable capacity
De Miera et al. (2008)	Spain	4.75-12.44 €/MWh (average price reduction, wind)
Sensfuß et al. (2008)	Germany	1.7-7.83€/MWh (average price reduction, renewables)
Gelabert et al. (2011)	Spain	2€/MWh (marginal price reduction from a 1GWh increase of renewable generation)
Traber and Kemfert (2011)	Germany	3.7€/MWh (average price reduction, wind)
Woo et al. (2011)	Texas	1.5-6.1 $/MWh (marginal price reduction from a 1GWh increase wind generation)
Würzburg et al. (2013)	Austria and Germany	7.6 €/MWh (average price reduction, renewables)
Clò et al. (2015)	Italy	2.3€/MWh (marginal price reduction from a 1GWh increase of solar generation) 4.2€/MWh (marginal price reduction from a 1GWh increase of wind generation)
Woo et al. (2016)	California	4.0-5.3 $/MWh (marginal price reduction from a 1GWh increase of solar generation) 3.3-3.4 $/MWh (marginal price reduction from a 1GWh increase of wind generation)
Abrell et al. (2019)	Germany and Spain	1.2 €/MWh (marginal price reduction from a 1GWh increase of wind generation, Germany) 2.6 €/MWh (marginal price reduction from a 1GWh increase of wind generation, Spain)
Macedo et al. (2020)	Portugal	Price decreases by 0.06% when wind generation increases by 1%
Bushnell and Novan (2021)	California	~0.4 $/MWh (marginal price reduction from a daily 1GWh increase of renewable generation)
Mwampashi et al. (2021)	Australia	1.3 AUD/MWh (marginal price reduction from a 1GWh increase of wind generation)

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Table A2 continued from previous page

Paper	**Region**	**Merit Order Effect**
Peña et al. (2022)	Spain	Wind plant remuneration decrease by 0.655€/MWh when wind penetration increases by 1%
Petersen et al. (2022)	Spain	~2 €/MWh (marginal price reduction from a 1GWh increase of wind generation)

A.2 Additional Tables

Table A3: Effects of RE on exports (MWh exports per MWh of RE)

	(1) Spain to France	(2) France to Spain
β_{Wind}	0.07***	0.04***
	(0.01)	(0.01)
β_{Solar}	0.007	0.05
	(0.053)	(0.03)
Exports_{Wind}	3.3***	0.76***
	(0.48)	(0.19)
Exports_{Solar}	0.05	0.3
	(0.42)	(0.2)

Note: β coefficients indicate the marginal effect of wind and solar energy on exports from Spain to France and from France to Spain. Exports is the yearly average impact of wind and solar on exports measured in TWh and calculated by $Exports = \beta \bar{RE}$ with $\bar{RE}$ being wind or solar average yearly generation.

Table A4: Emissions regression results - Augmented local linear

Variable	Spanish emissions	French emissions
	(1)	(1)
Wind Spain	-0.468***	0.019
	(0.010)	(0.011)
Wind Spain $\times 1\{t \geq 10/2015\}$	0.073**	-0.042**
	(0.018)	(0.006)
Wind France	0.015	-0.084*
	(0.025)	(0.025)
Load Spain	0.173**	0.008
	(0.038)	(0.026)
Load France	-0.003	0.119**
	(0.030)	(0.015)
Cost Ratio	-298.249	-522.500
	(5943.883)	(1598.030)
Hours of day FE	YES	YES
Day of week FE	YES	YES
Month of Year FE	YES	YES
Fully interacted	YES	YES
N	1464	1464
R-squared	0.787	0.605

Note: Results for equations 5 and 6. Augmented local linear: the impacts of seasonality controls are estimated using the two-years data window and the residuals are saved. Then a local linear specification is estimated using the residuals within a narrow 30 days band-width. Coefficients can be interpreted as tCO_2/MWh. Newey–West standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A5: Emissions regression results - Control variables are not interacted with the indicator

Variable	Spanish emissions	French emissions
	(1)	(1)
Wind Spain	-0.537***	0.013
	(0.025)	(0.011)
Wind Spain $\times 1\{t \geq 10/2015\}$	0.167***	-0.035**
	(0.040)	(0.017)
Wind France	-0.025	-0.198***
	(0.021)	(0.016)
Load Spain	0.499***	0.035
	(0.022)	(0.021)
Load France	-0.002	0.120***
	(0.012)	(0.009)
Cost Ratio	-767.032***	-501.011***
	(103.045)	(252.223)
Hours of day FE	YES	YES
Day of week FE	YES	YES
Month of Year FE	YES	YES
Fully interacted	NO	NO
N	29,228	29,228
R-squared	0.899	0.838

Note: Results for equations 5 and 6. BIC-chosen global polynomial. Controls are not interacted with the indicator variable. Coefficients can be interpreted as tCO_2/MWh. Newey–West standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A6: Emissions regression results - Daily aggregation

Variable	Spanish emissions	French emissions
	(1)	(1)
Wind Spain	-0.580***	0.026
	(0.025)	(0.016)
Wind Spain $\times 1\{t \geq 10/2015\}$	0.167***	-0.081**
	(0.040)	(0.020)
Wind France	-0.031	-0.230***
	(0.026)	(0.019)
Load Spain	0.645***	0.098***
	(0.031)	(0.025)
Load France	-0.003	0.135***
	(0.013)	(0.010)
Cost Ratio	-52328.4	-56546.94
	(68773.74)	(41971.92)
Day of week FE	YES	YES
Month of Year FE	YES	YES
Fully interacted	YES	YES
N	703	703
R-squared	0.921	0.867

Note: Results for equations 5 and 6 with daily aggregation. BIC-chosen global polynomial. All controls are interacted with the indicator variable. Coefficients can be interpreted as tCO_2/MWh. Newey–West standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

A.3 Additional Figures

Figure A1: Average monthly electricity demand in Spain and France and Wind generation in Spain (GWh)

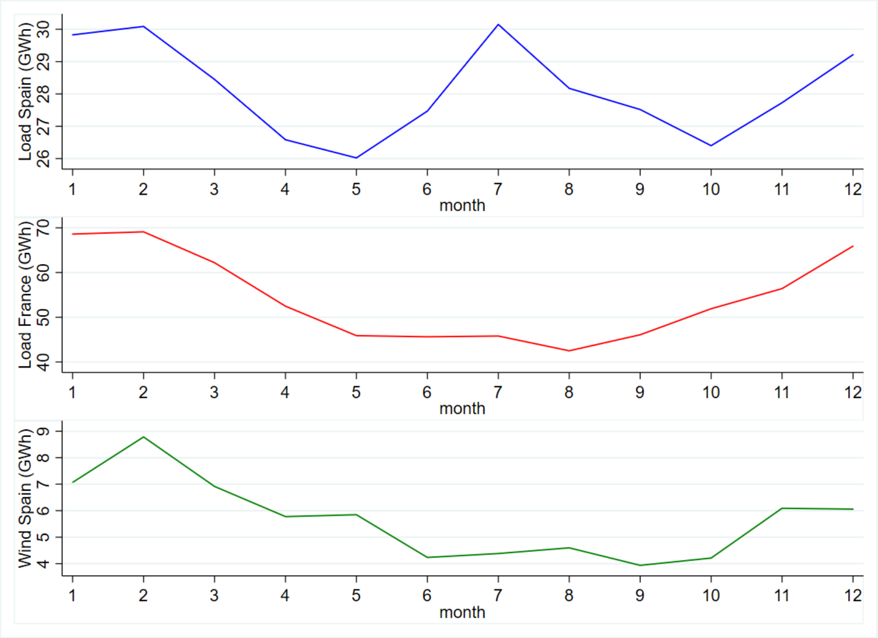


Figure A2: Average daily photovoltaic generation in Spain and France (GWh)

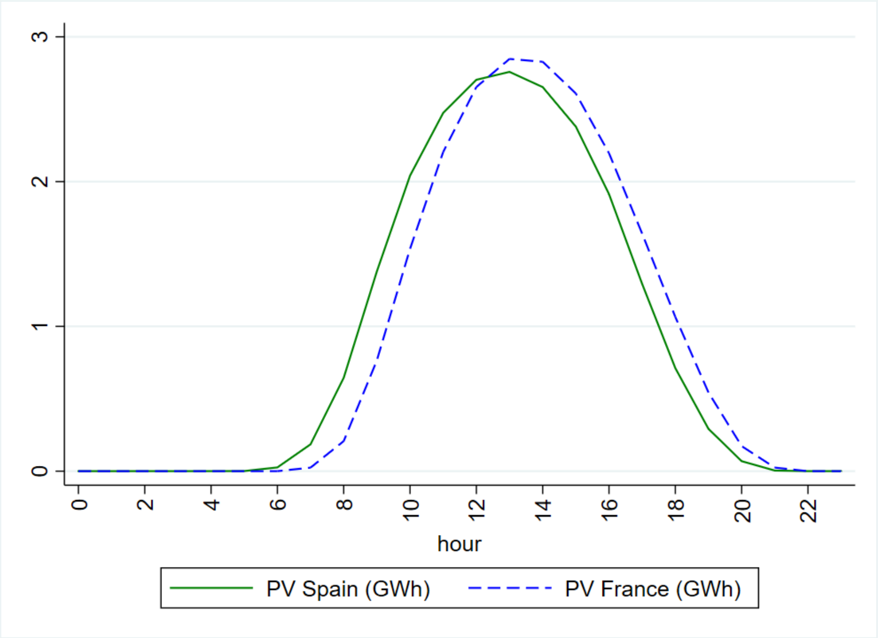
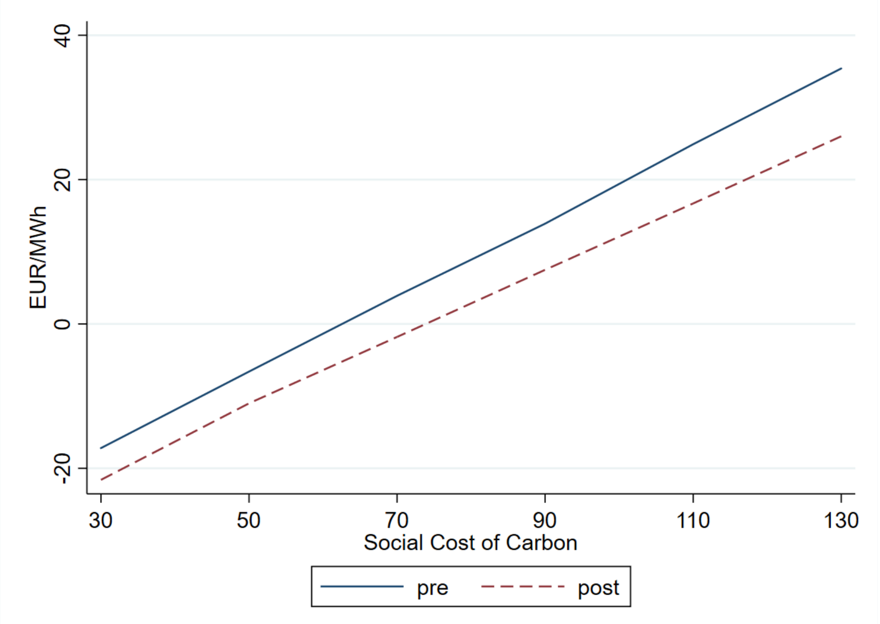


Figure A3: Marginal Surplus Effects of Wind with varying Social Cost of Carbon



Note: This figure illustrates effect of a marginal increase in wind generation on economic surplus as a function of the social cost of carbon. The figure shows the break-even social costs of carbon of wind promotion before and after expansion.