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When markets merge: evidence from Ireland's integration with the European wholesale electricity market

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How does electricity market integration affect cross-border electricity flows, wholesale prices and renewable electricity generation? We employ a synthetic control method to contribute to literature on electricity market integration using the 2018 integration of Ireland's Single Electricity Market with the European market as an empirical case study. Results indicate a decrease in inefficient electricity flows between Ireland and Great Britain and an increase in the level of market integration with Great Britain. We find no effect on the average wholesale electricity price in Ireland, and this may reflect interconnector congestion. We also find no short-term increase in renewable generation.

Key words: market integration; electricity; energy; wholesale electricity market; synthetic control method.

JEL codes: Q41; Q48; F15; L94; L98.

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1. Introduction

The energy crisis in Europe, sparked in 2021 when gas demand recovered quicker than anticipating following the COVID-19 pandemic and exacerbated by the 2022 invasion of Ukraine by Russia, further emphasised the importance of electricity market design in a decarbonising energy system. How does electricity market integration affect cross-border electricity flows, wholesale prices and renewable electricity generation? While these questions have been examined on a theoretical level by many studies, real-world opportunities to empirically test these theoretical predictions are more elusive.

In this paper, we employ high-frequency electricity market data to examine the impact of market integration, using the October 2018 integration of Ireland's Single Electricity Market with the European Union (EU) Internal Energy Market as a case study. Ireland represents an intriguing case study as it is a relatively isolated system, thus reducing confounding factors, and has a relatively high share of renewable electricity and may therefore preview challenges related to renewables before they arise elsewhere.

We assess the impact of Ireland's market integration with Europe on the level and efficiency of cross-border electricity flows. In line with trade theory, Batalla et al. (2019) found that market integration increased electricity trade among members but reduced trade between non-members. Newbery et al. (2016) and Montoya et al. (2020) found increases in trading efficiency due to interconnector coupling, with inefficient flows from higher- to lower-price markets occurring less frequently.

Our paper also tests for an impact on the wholesale electricity price. Competition and scale effects of regional market integration should lead to more efficient firms, lower and less volatile prices and thus increased welfare (Batalla et al., 2019; Cassetta et al., 2022a; Zachmann, 2008). Cassetta et al. (2022b) noted that a lower average price and a higher level of price convergence have historically been regarded as primary performance indicators of the EU Internal Energy Market. Cicala (2022) found that increases in electricity trade reduced production costs, and Dahlke (2020) showed a negative relationship between electricity trade and the wholesale price. Karahan et al. (2024) found an increase in financial efficiency due to market integration. However, as electricity trade is entirely constrained by transmission infrastructure, congested interconnections will prevent price harmonisation between integrated markets (Batalla et al., 2019; LaRiviere & Lyu, 2022). Ryan (2021) showed that market competitiveness was lower during hours of congestion. Saez et al. (2019) found that congestion occurred more frequently where renewable penetration was high, and Fell et al. (2021) demonstrated that congestion influenced emission reductions from integrating wind into the generation mix.

In addition, we examine the degree of market integration between Ireland and neighbouring Great Britain by testing the Law of One Price (Helpman & Krugman, 1985), or price convergence. The Law of One Price, previously tested in other markets such as natural gas (Bastianin et al., 2019; Renou-Maissant, 2012; Robinson, 2007), cars (Goldberg & Verboven, 2005) and Bitcoin (Pagnottoni & Dimpfl, 2019), has been assessed in integrated electricity markets by several studies. For example, Böckers & Heimeshoff (2014), Cassetta et al. (2022a), Cassetta et al. (2022b), Castagneto-Gissey et al. (2014), Ciferri et al. (2020), de Menezes & Houllier (2016), Robinson (2007), Saez et al. (2019) and Zachmann (2008) have all examined price convergence as a measure of electricity market integration in Europe, with results generally finding that while there had been some convergence between markets, full integration remained elusive. Our study of market integration is also linked with a literature on transmission infrastructure expansion (Abrell & Rausch, 2016; Borenstein et al., 2000; Bushnell, 1999; Joskow & Tirole, 2000, 2005; Urquijo & Paraschiv, 2023; Yang, 2022). For example, Gonzales et al. (2023) found price convergence due to new interconnections.

Finally, our paper asks whether market integration had an impact on renewable electricity generation in Ireland. By facilitating the balancing of differences between renewable-intensive regions and demand centres, electricity market integration should increase market entry incentives for more environmentally efficient generation units (Batalla et al., 2019; Gonzales et al., 2023).

Using a novel panel dataset, we employ the synthetic control method to test for an impact on trade flows, the wholesale price and renewable generation. This approach, hailed by Athey & Imbens (2017) as a major innovation in causal inference, is based on a data-driven selection process for constructing a control group from comparison units.

We also use national holidays as exogenous shocks to electricity demand to assess the degree of wholesale market integration between Ireland and Great Britain. Using regressions of hourly data, we examine whether the wholesale price in Ireland was reduced by national holidays that occurred only in Great Britain. This follows the approach of Böckers & Heimeshoff (2014), who pointed out that exogenous shocks are required to robustly test for market integration as electricity prices are influenced by a multitude of factors, some of which are common across market zones. Other studies of electricity price convergence have relied on unit root tests, beta convergence, sigma convergence, club convergence and cointegration.

We find an immediate negative effect on inefficient cross-border electricity flows that can be attributed to Ireland's market integration with Europe. These results are in line with Montoya et al. (2020) and Newbery et al. (2016). However, contrary to theoretical predictions, we do not find evidence of an impact on electricity trade, the wholesale price or renewable generation. We show that congested transmission infrastructure may have been a factor in these findings.

Our study finds that the degree of integration between Ireland and Great Britain was higher following Ireland's integration with the wide European market, similar to the results of Böckers & Heimeshoff (2014).

In Section 2, we describe the synthetic control method, the exogenous demand shock approach, and the collation of our comprehensive panel of high-frequency electricity market data. Section 3 outlines the energy policy context in Ireland and the EU. Results are presented in Section 4, while conclusions and policy implications are discussed in Section 5.

2. Background

2.1. Where does market integration fit in European energy policy?

Leading countries in reforming electricity markets include Australia, Argentina, Chile and New Zealand (Jamasb & Pollitt, 2005), while the United Kingdom (UK) and Norway were the first European countries to liberalise electricity markets (Glachant & Ruester, 2014). The EU Internal Energy Market can be traced back to 1988, when the European Commission first considered how the budding European Single Market could be applied to the supply of electricity and gas (European Commission, 1988). Since then, a series of Commission directives in 1996 (96/92/EC), 2003 (03/54/EC) and 2009 (09/72/EC) have underpinned extensive institutional reform and market integration (Newbery et al., 2018; Pollitt, 2019). The goals in establishing the EU Internal Energy Market as a competitive, integrated market have been reconciling wholesale prices and enhancing security of supply (Castagneto-Gissey et al., 2014; Glachant & Ruester, 2014). It is now one of the largest integrated electricity markets in the world, with 577 TWh of electricity generated during the second quarter of

2024. Of this, 52 per cent came from renewable sources, 24 per cent from fossil fuels and the remaining 24 per cent from nuclear (European Commission, 2024).

Internationally, progress in reforming wholesale electricity markets has not been uniform. For example, political enthusiasm for electricity market reform in the US was dampened by the 2000-01 electricity crises in California and 2003 blackouts in New York (Jamasb & Pollitt, 2005). In Europe, progress has varied between zones and between market stages, with day ahead markets proving easier to integrate than intraday and balancing markets (Newbery et al., 2016).

While electricity networks are considered natural monopolies in need of regulation, electricity generation and trade are viewed as potentially competitive activities. Electricity market reform has thus involved the unbundling of these activities and the introduction of an integrated, competitive wholesale market (Batalla et al., 2019; Glachant & Ruester, 2014; Joskow & Tirole, 2000). The use of market mechanisms to determine electricity generation essentially integrates dispatch operations into an electricity auction, where previously a centralised balancing authority would have relied on cost estimates to design dispatch algorithms (Cicala, 2022).

Prior to market reform in Europe, cross-border electricity flows were managed by vertically integrated monopolies bound by long-term bilateral contracts (Batalla et al., 2019; Joskow & Tirole, 2000). Interconnector capacity was sold before the day ahead market opened, meaning traders had to predict price differentials across interconnectors. This ran the risk of trade turning out to be unprofitable by the time it occurred, leading to interconnectors being under-utilised or electricity sometimes flowing from a higher-price to a lower-price zone (Newbery et al., 2016).

The connection of various national electricity markets requires a combination of physical interconnections and technical arrangements (de Menezes & Houllier, 2016; Jamasb & Pollitt, 2005). The technical blueprint for integrating European electricity markets is the Target Electricity Model (TEM), in which interconnectors are coupled across borders, their capacities are optimised, and electricity is efficiently allocated across the EU by the Euphemia (Pan-European Hybrid Electricity Market Integration Algorithm) single auction platform (Newbery et al., 2016). With Single Day Market Coupling (SDAC), European Transmission System Operators (TSOs) aim to create a single cross-zonal day ahead electricity market that uses Euphemia for price coupling. In 2014, the day ahead markets of

17 European countries were coupled using the SDAC mechanism. Other key features of the TEM include close to real-time energy trading, a hedging facility for regional price differences that stem from congestion, and integrated balancing arrangements (EirGrid, 2016).

2.2. What is Ireland's Integrated Single Electricity Market (I-SEM)?

The electricity grid on the island of Ireland (encompassing the Republic of Ireland and Northern Ireland) represents a fascinating case study as it is a relatively small, synchronous system that is currently linked to Europe only via Great Britain by the Moyle Interconnector between Northern Ireland and Scotland and the East-West Interconnector between Ireland and Wales. This relative isolation serves to reduce confounding factors in any analysis of market design.

As of the second quarter of 2024, Ireland had the highest quarterly average wholesale electricity price in the EU at EUR101 per MWh. By comparison, the average was EUR77 per MWh in neighbouring Great Britain, EUR68 per MWh across the whole EU and a mere EUR31 per MWh in France (European Commission, 2024). In 2023, the predominant sources of electricity generation in Ireland were natural gas and wind at 49 and 37 per cent respectively (IEA, 2024). This relatively high share of renewable electricity also makes Ireland an interesting case study as it may experience challenges related to renewables that will later arise in other countries.

From October 2018, the Integrated Single Electricity Market (I-SEM) went live on the island grid to replace existing arrangements with multiple markets for different timeframes and separate clearing and settlement mechanisms. The new I-SEM arrangements adopted the European TEM and were designed to integrate Ireland's existing Single Electricity Market with European markets and optimise the use of its two interconnectors. A centralised pool market was replaced by a range of more granular markets: day ahead, intraday, balancing, forwards and capacity markets (EirGrid, 2016).

This more granular market structure made I-SEM much more flexible than its predecessor, which should better facilitate the integration of renewable energy by allowing intermittent generators to adjust their positions closer to the time of delivery (EirGrid, 2016). O'Sullivan et al. (2014) examined the potential implications of higher penetration of wind for the security of Ireland's power system.

A Single Electricity Market for wholesale electricity had been in place on the island of Ireland since 2007. This original Single Electricity Market was a gross mandatory pool market that had no direct integration with European markets. Wholesale prices were determined by a central pool mechanism to which suppliers bid their marginal cost, and balancing was handled via central dispatch. An absence of mechanisms for forward trading or price hedging may have led to inefficient price signals.

Prior to I-SEM, one of the main issues was the ex-post price calculation that meant a British electricity exporter had to guess the Irish price level when deciding whether to export. When the final price was calculated 4 days post-delivery, the exporter will have occasionally found, to their dismay, that the electricity had inefficiently flowed from a higher- to a lower-price market (Viljainen et al., 2013). Compounding this, Nepal & Jamasb (2012) argued that the insufficient level of interconnection was particularly concerning due to the isolated and concentrated nature of the Irish market, as limited competition could provide opportunities for market power abuse.

3. Methods

We tested six hypotheses in this study, and the first two were based on cross-border electricity flows. I-SEM improved the market arrangements for trading electricity via Ireland's interconnectors with Great Britain, and this could be viewed more generally as a reduction in electricity trade barriers. Trade theory suggests this should have increased cross-border flows, giving us our first hypothesis to test. More specific to the context of electricity trade, I-SEM's optimisation of interconnector use rather than requiring electricity exporters to predict the price differential should also have reduced the incidence of electricity flowing inefficiently from the higher-price to the lower-price zone, and this formed our second hypothesis.

Hypothesis 1: I-SEM increased cross-border electricity flows between Ireland and Great Britain.

Hypothesis 2: I-SEM increased the efficiency of cross-border electricity flows between Ireland and Great Britain.

The next set of hypotheses focused on one of the cornerstones of a competitive wholesale electricity market, the day ahead price. Ireland's integration with the European wholesale electricity market also presented an opportunity to test theoretical predictions such as the Law of One Price. In Hypotheses 3 and 4, therefore, we tested whether this integration reduced the wholesale price or its volatility in Ireland.

Hypothesis 3: I-SEM reduced the average wholesale day ahead price in Ireland.

Hypothesis 4: I-SEM reduced volatility in the wholesale day ahead price in Ireland.

For price convergence in Hypothesis 5, we focused on pair-wise price convergence with Great Britain. While Ireland's integration was with the wider European market, its only physical interconnections were with Great Britain and any possible convergence towards another zone's price should be towards that of Great Britain in the first instance.

Hypothesis 5: I-SEM led to a convergence of wholesale day ahead prices in Ireland and Great Britain.

Finally, in Hypothesis 6, we tested the theory that electricity market integration increases incentives for renewable electricity generation to enter the market.

Hypothesis 6: I-SEM increased renewable electricity generation in Ireland.

All six hypotheses were tested against the null of I-SEM having no effect.

3.1.Data

We collated a novel panel dataset combining legacy data from the Single Electricity Market Operator (SEM-O) in Ireland with data from the European Network of Transmission Operators for Electricity (ENTSO-E) Transparency Platform. ENTSO-E is the European association of the national transmission system operators that manage the electricity grids across the continent and is a rich source of high-frequency pan-European electricity market data. The European electricity market is divided into 'bidding zones', with zones typically representing countries although some countries are split into multiple zones.

Hourly, zone-level data was collected for the period between 6 January 2015 and 31 December 2020. I-SEM went live on the island of Ireland on 1 October 2018, giving 45 months of data before and 27 months after integration with the European market. We set this study period to start from the launch of the ENTSO-E Transparency Platform, and end prior to the UK's exit from the EU Single Market at the start of 2021 as well as the European energy crisis that began later that year. Table 1 displays summary statistics for our comprehensive hourly panel dataset. Further details on these variables, including our approach to missing observations, are available in Appendix A.

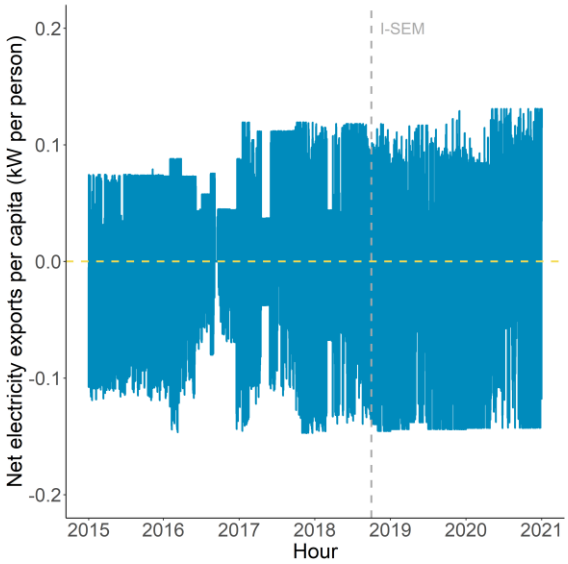
Table 1: Descriptive statistics, hourly panel dataset 2015-2020

Statistic	N	Mean	St. Dev.	Min	Max
Day ahead price (EUR)	1,259,136	36.00	17.89	-500.00	874.01
Forecast load (kW) per capita	1,259,136	1.87	1.46	0.08	9.60
Actual load (kW) per capita	1,259,136	1.87	1.45	0.13	18.01
Export (kW) per capita	1,259,136	1.00	2.44	0.00	19.99
Import (kW) per capita	1,259,136	0.51	0.74	0.00	8.66
Renewable electricity (kW) per capita	1,259,136	0.23	0.53	0.00	8.65
Hydropower (kW) per capita	1,259,136	1.51	2.92	0.00	18.28
Unavailable generation (kW) per capita	1,259,136	1.79	2.98	0.00	21.89

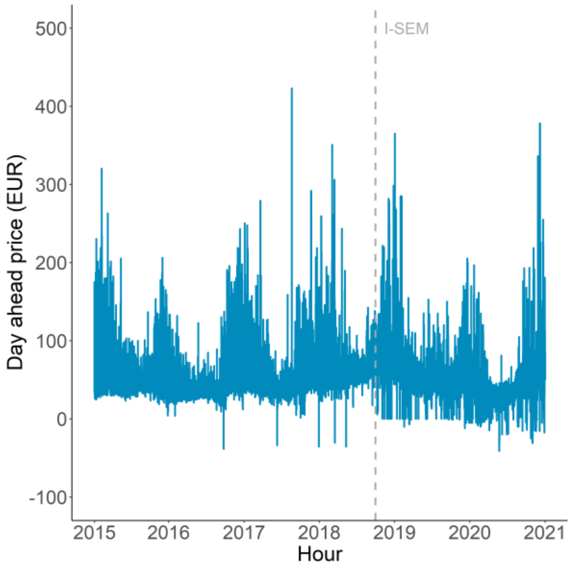
Notes: 'N' denotes number of observations, 'St. Dev.' denotes standard deviation.

Figure 1 displays hourly market data for Ireland's Single Electricity Market during the study period. A preliminary inspection of this raw data suggests that interconnector flows have increased since the launch of I-SEM (Figure 1a), with the volume on the East-West Interconnector regularly at capacity in both directions. Meanwhile, the hourly day ahead wholesale price (Figure 1b) is characterised by seasonal and daily patterns that have not changed significantly since market integration, although electricity prices appear to have been briefly lower and less volatile during COVID-19.

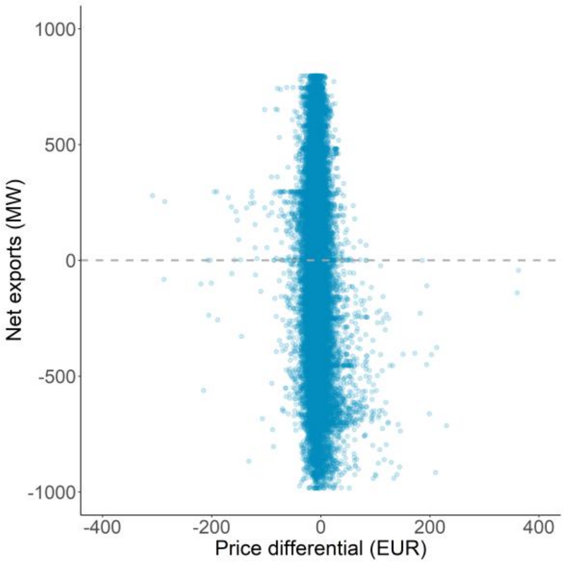
Figures 1c and 1d illustrate the efficiency of cross-border flows between Ireland and Great Britain before and after I-SEM by plotting net exports to Great Britain against the price differential, with each point representing an hour. These figures demonstrate that there has been a change in the pattern of trade, in addition to the increase in trade suggested by Figure 1a. Interconnectors are being used efficiently when electricity flows from the lower-price to the higher-price zone, represented by the top left and bottom right quadrants in Figures 1c and 1d. It is evident from this raw data that electricity flowed against the price differential more regularly before I-SEM, with net exports better aligned with the price differential post-integration in Figure 1d.



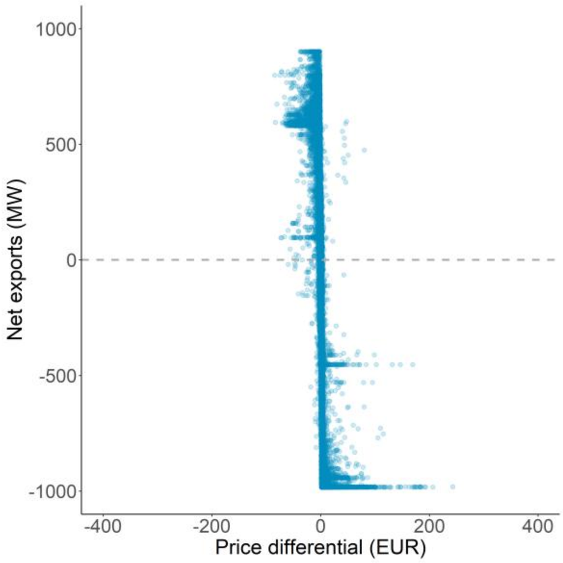
(a) Net electricity exports per capita to Great Britain. Grey vertical line shows I-SEM launch.



(b) Day ahead price. Grey vertical line shows I-SEM launch.



(c) Net exports and price differential to Great Britain, before I-SEM.



(d) Net exports and price differential to Great Britain, after I-SEM.

Figure 1: Hourly market data, Ireland Single Electricity Market 2015-2020. Source: Author's analysis; ENTSO-E; SEM-O.

These patterns in the raw data were worthy of further analysis to establish whether any causality could be attributed to electricity market integration. This required estimating what would have happened had I-SEM not been introduced. For this task, we turned to the synthetic control method.

Various metrics of cross-border flows (in)efficiency were discussed in detail by Montoya et al. (2020). The simplest measure of inefficiency, known as Unweighted Flows Against the Price Differential (UFAPD), divides the number of inefficient flows (where electricity flows from the higher- to the lower-price zone) by the total number of flows in a given period. An alternative is the Weighted Flows Against the Price Differential (WFAPD) metric, where all flows are weighted by the absolute value of the price differential. We calculated both UFAPD and WFAPD and subjected them to a synthetic control analysis.

3.2.Synthetic control method

Abadie & Gardeazabal (2003) introduced the synthetic control method as a novel approach to causal inference, applying it to show terrorism had reduced GDP per capita in the Basque Country. Building on this, Abadie et al. (2010) demonstrated the method's wide applicability to comparative studies using a small number of large, aggregated units such as cities, states or countries by assessing state-level tobacco policy in the US. The method has since become popular in economic literature (for example Acemoglu et al., 2016; Bohn et al., 2014; Cunningham & Shah, 2018; Kleven et al., 2013; Peri & Yasenov, 2019; Pinotti, 2015), and Abadie et al. (2015) exhibited its suitability for small-sample comparative studies in political science.

Abadie (2021) presented a detailed overview of the synthetic control method. In summary, unlike other comparative methods such as difference-in-differences, it formalises the selection process for constructing a control group from comparison 'units' (for example, countries or states). This involves calculating a set of unit weights, such that the synthetic control group is a weighted average of units in the 'donor pool'. Weights are restricted to be non-negative and to sum to 1, and most units tend to be attributed a negligible weight.

Abadie & Gardeazabal (2003) and Abadie et al. (2010) proposed that weights be chosen such that the resulting synthetic control group best resembles the treated unit's pre-intervention values for predictors of the outcome variable. These predictors, in turn, are weighted to minimise the mean squared prediction error (MSPE) of the synthetic control with respect to the affected unit's outcome variable in the pre-intervention period. In other words, predictor variables are weighted to reflect their relative importance in predicting the pre-treatment outcome.

The treatment effect is then calculated as the post-treatment difference in the outcome variable between the treated unit and the synthetic control group. For inference, Abadie et al. (2015) estimated a set of placebo effects on all other units, with the treatment effect deemed significant if it was extreme relative to the permutation distribution of the placebo effects.

The synthetic control method boasts several advantages over regression-based methods. First, unlike in a regression, there is no extrapolation as unit weights are non-negative and sum to 1. Second, it is very clear from the pre-treatment period how successfully the synthetic control mirrors the treated unit. Third, presenting unit weights make the composition of the counterfactual highly transparent. Fourth, while the donor pool may include many units, the synthetic control group is relatively sparse with most units receiving a negligible weight (Abadie, 2021).

Abadie (2021) outlined how a treatment effect may be difficult to detect in data characterised by a high level of volatility using the synthetic control method, and hourly electricity market data is highly volatile. Therefore, when using this method, we aggregated all hourly data to the monthly level, giving a monthly panel of bidding zones. We included 23 bidding zones in our donor pool based on when they integrated with the European market and data availability (see Appendix A for details).

Given the prominent role of natural gas in generating electricity, the wholesale price of natural gas is a key factor in day ahead electricity prices. As natural gas is largely traded via international trading hubs such as the Title Transfer Facility in the Netherlands, its wholesale price varies mainly over time rather than between electricity market bidding zones. Therefore, the wholesale gas price faced by electricity generators can be treated as a time fixed effect. Based on this, for our synthetic control method analysis of the day ahead price and its volatility, we first ran fixed effects regressions including only month fixed effects, and employed the residuals of these regressions as the outcome variable in the synthetic control analysis. Specifically, we ran the following regression using our aggregated monthly panel:

$$\log p_{i,m} = \alpha + month_m + \epsilon_{i,m} \qquad (1)$$

In Equation 1, the natural log of the average day ahead wholesale price of zone i in month m is the outcome variable, while the variable $month_m$ specifies the month of the study period (for example, January 2017). Having estimated this regression, we then used the zone- and month-specific residual, $\epsilon_{i,m}$, as the outcome variable for our synthetic control analysis of day ahead prices. Essentially, this applied the synthetic control method only to the remaining variation in day ahead prices and price volatility that could not be explained by common time-varying factors such as the global wholesale price for natural gas. To support this approach, we show that the estimated month fixed effects largely tracked the global price of natural gas in the EU throughout the study period (see Appendix B).

3.3. Market integration

Böckers & Heimeshoff (2014) pointed out that electricity prices are influenced by a multitude of factors, some of which are common across market zones, and that exogenous shocks are thus required to robustly test for integration. They proposed relying on national holidays that are not common across zones as exogenous shocks to electricity demand. A relatively high level of integration between two market zones should imply that if one zone exogenously and unilaterally decreased its electricity demand due to a national holiday, the wholesale price in the other zone should fall as its demand would be unchanged but it can now draw on the excess supply in the zone enjoying a holiday.

To test for wholesale market integration between Ireland and Great Britain, we followed this approach. Specifically, we estimated the following regression using ordinary least squares:

$$\log(p_{i,t}) = \alpha + \beta\, holiday_{i,t} + \gamma\, holiday_{j,t} + year_t + calendarmonth_t + dayofweek_t + hourofday_t + \log(gasprice_t) + \epsilon_t \tag{2}$$

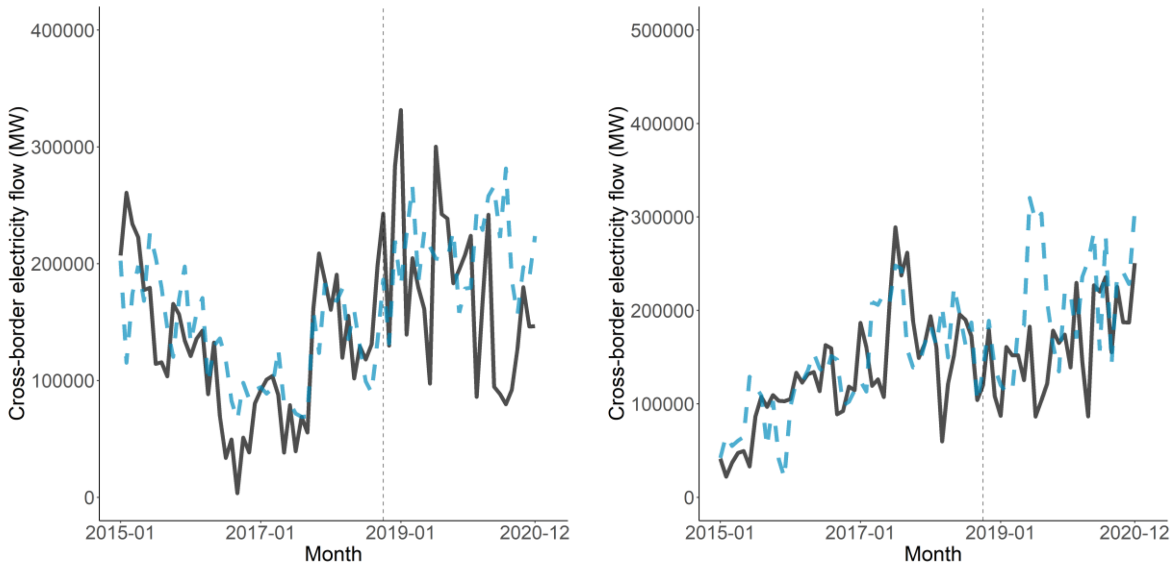
In Equation 2, the natural log of the day ahead wholesale price of domestic zone i in hour t is the outcome variable. The variable $holiday_{i,t}$ records whether hour t falls on a national holiday in zone i, while the variable $holiday_{j,t}$ records whether the hour falls on a national holiday in foreign zone j that is not shared by zone i. The natural log of natural gas prices and fixed effects for the year, calendar month, day of the week and hour of the day are also included as control variables.

For this approach to be valid, the β coefficient should be negative as this shows that the day ahead price in zone i was reduced by a domestic national holiday and its associated reduction in demand. If the price was not reduced by a domestic holiday, how could it be affected by a foreign holiday? The γ coefficient, meanwhile, indicates whether the price was reduced by a foreign holiday, and this is the measure of market integration. We estimated this regression for Ireland's day ahead price on data spanning the entire study period and separately on data before and after the launch of I-SEM.

4. Results

4.1. Synthetic control analysis

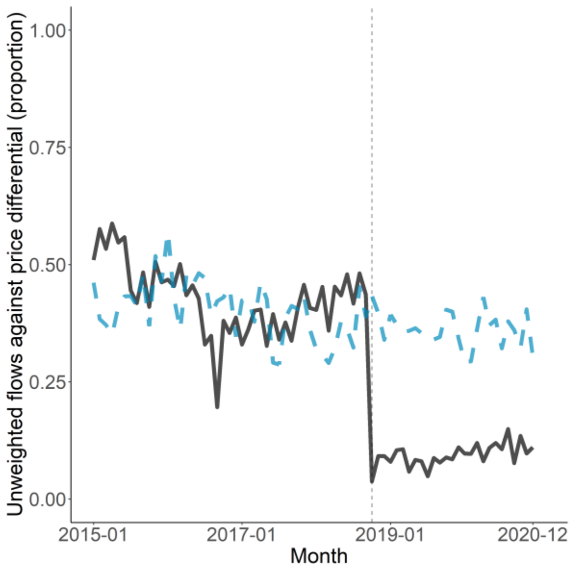
Figure 2 displays synthetic control method results for monthly cross-border electricity flows between Ireland and Great Britain, testing Hypothesis 1. The synthetic control group (blue dashed line) tracks the observed data (black solid line) well prior to market integration. However, no sustained differences emerge between the control group and observed data post-integration, meaning we cannot reject the null of no effect on cross-border flows. In other words, our synthetic Ireland indicates that electricity imports from Great Britain would have remained high, and exports to Great Britain would have continued to increase, regardless of market integration.



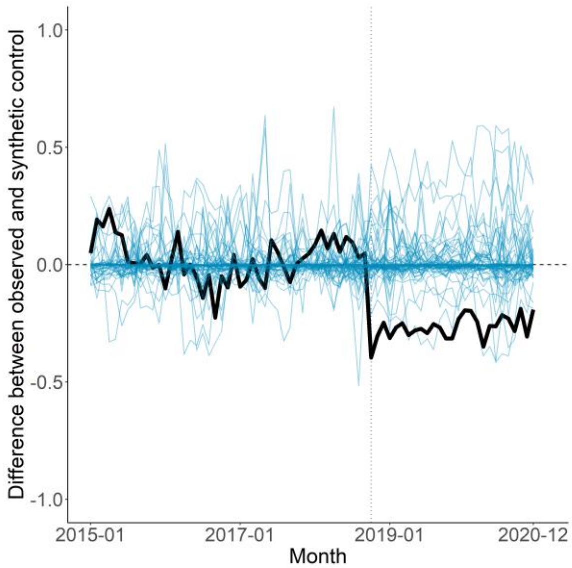
(a) Great Britain to Ireland (b) Ireland to Great Britain

Figure 2: Synthetic control method results, cross-border flows per capita. Black solid line shows observed data, blue dashed line shows synthetic control group, grey vertical line shows I-SEM launch. Source: Authors' analysis; ENTSO-E.

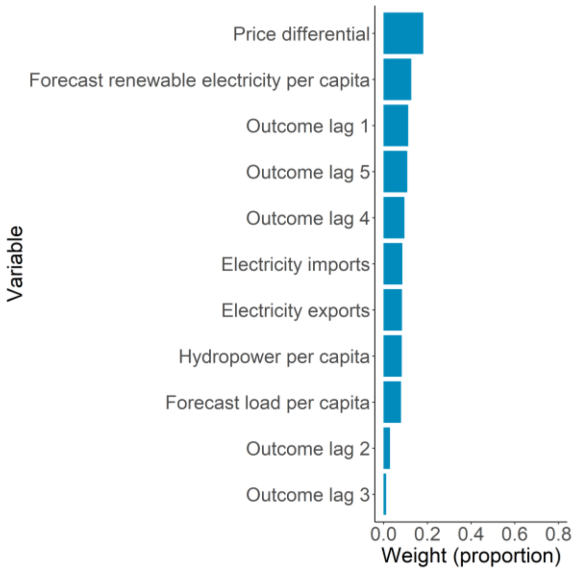
Clearer results are evident for the inefficiency of cross-border electricity flows between Ireland and Great Britain in Figure 3. A substantial, immediate and persistent observed decrease in UFAPD that is not echoed by the synthetic control group is apparent in Figure 3a. Based on this, the treatment effect, which is the difference between observed data and the control group, is plotted in Figure 3b (black solid line) alongside placebo treatments for all other bilateral flows (blue thin lines). That the negative effect on inefficient flows between Ireland and Great Britain is more extreme than almost all placebo treatment effects indicates that the treatment effect is significant, representing evidence in favour of Hypothesis 2. We find similar results for the WFAPD metric.



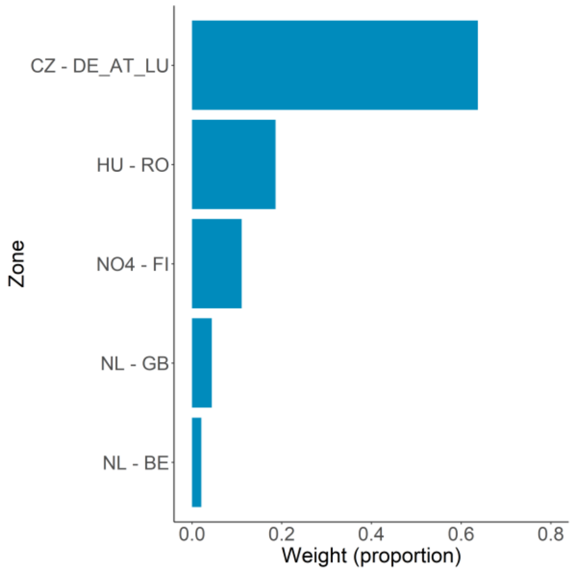
(a) Trends, observed data (black solid line) and synthetic control group (blue dashed line). Grey vertical line shows I-SEM launch.



(b) Difference between observed data and synthetic control group, Ireland-Great Britain (black solid line) and placebos (blue lines). Grey vertical line shows I-SEM launch.



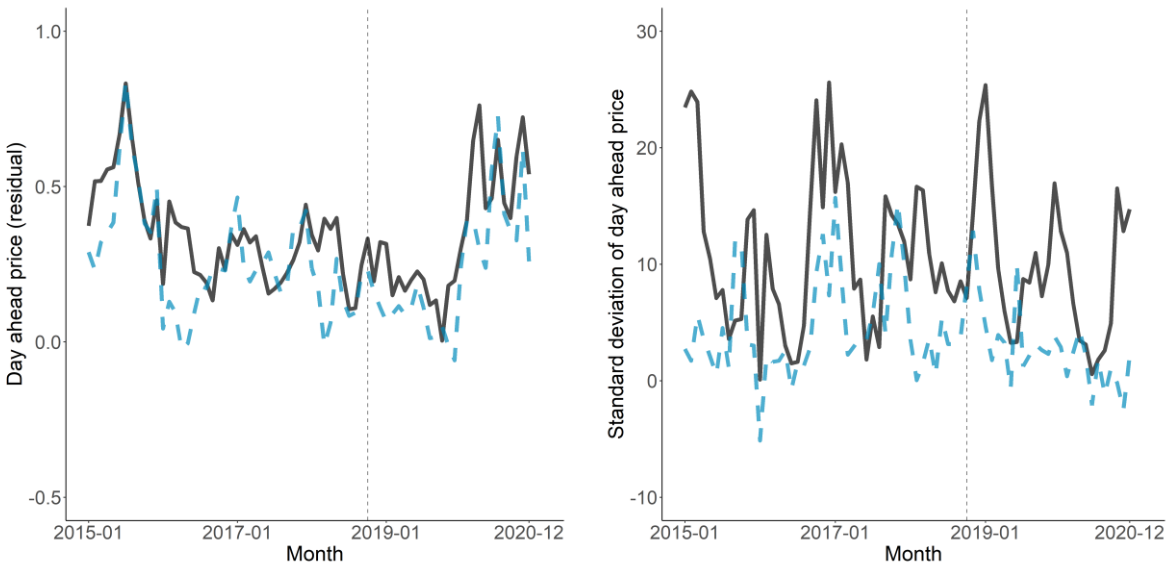
(c) Variable weights



(d) Unit weights

Figure 3: Synthetic control method results, efficiency of cross-border electricity flows. Sources: Authors' analysis; ENTSO-E; SEM-O.

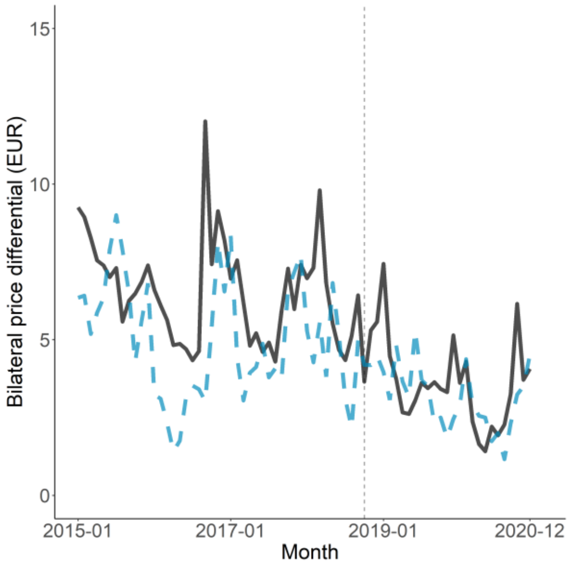
Figure 3c indicates the weights attributed by the synthetic control method to explanatory variables for flow inefficiency as measured by UFAPD, with weights evenly distributed and most weight given to the bilateral price differential. The composition of the synthetic control group for flow inefficiency is summarised in Figure 3d, with synthetic Ireland-Great Britain bilateral flows constructed as a weighted average of bilateral flows between Czechia and Germany, Hungary and Romania, Norway 4 and Finland, Netherlands and Great Britain, and Netherlands and Belgium.



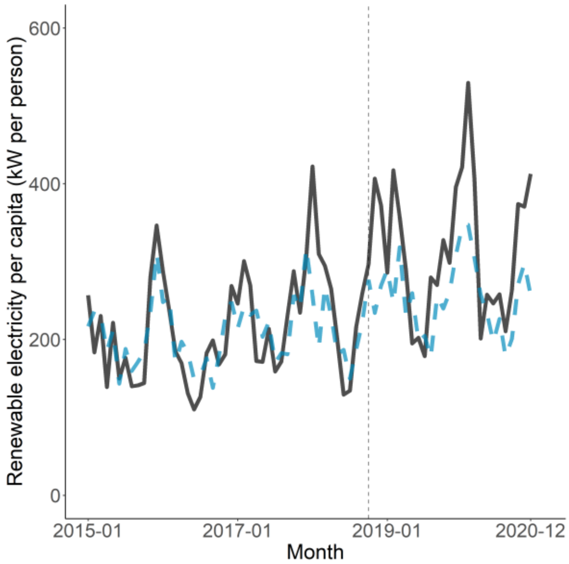
(a) Price (b) Price volatility

Figure 4: Synthetic control method results, day ahead price and price volatility in Ireland. Black solid line shows observed data, blue dashed line shows synthetic control group, grey vertical line shows I-SEM launch. Source: Authors' analysis; ENTSO-E, SEM-O.

While the efficiency of cross-border flows between Ireland and Great Britain may have increased, that no effect was found for the level of flows would suggest that the day ahead price was similarly unaffected as the mechanism for a price effect lies in these cross-border flows. Indeed, Figure 4 indicates no effect in either the day ahead price or its volatility (measured as the monthly standard deviation) in the Irish Single Electricity Market. The synthetic control group (blue dashed lines) tracks observed data (black solid line) before and after market integration for the residual of the day ahead price in Figure 4a. In the case of the residual standard deviation of the day ahead price in Figure 4b, the synthetic control group provides a relatively poor fit for observed data prior to market integration, meaning any post-treatment comparison is unreliable. Therefore, we cannot reject the null of no market integration effect in the cases of Hypotheses 3 or 4.



(a) Absolute deviation in day ahead price from cross-sectional bilateral average, Ireland and Great Britain



(b) Renewable electricity generation per capita

Figure 5: Synthetic control method results, Ireland-Great Britain price convergence and renewable electricity generation. Black solid line shows observed data, blue dashed line shows synthetic control group, grey vertical line shows I-SEM launch. Source: Authors' analysis; ENTSO-E, SEM-O.

In Figure 5a, while the absolute deviation of Ireland's day ahead price from the cross-sectional bilateral average price of Ireland and Great Britain appears to have decreased following the launch of I-SEM, our synthetic Ireland indicates that this would have happened anyway in the absence of market integration. Similarly, electricity generation from renewable energy continued to increase post-integration, with our results showing that this cannot be causally attributed to I-SEM.

4.2.Market integration analysis

We assessed the level of market integration between Ireland and the only other bidding zone that it shared a direct interconnection with during the study period, Great Britain, by examining day ahead electricity prices. First, in Figure 6, we followed the approach of Gonzales et al. (2023) and plotted the weekly average of the day ahead price difference between Ireland and Great Britain over time. This offers some descriptive evidence that while there continued to be considerable fluctuations, the average price difference was closer to 0 in the period following the launch of I-SEM than before.

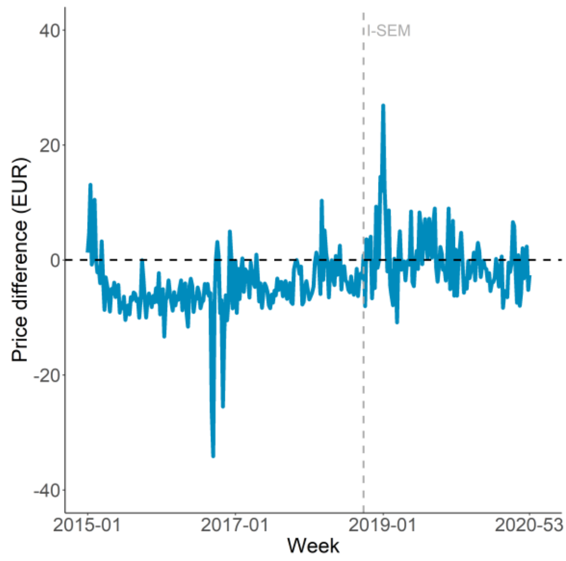


Figure 6: Weekly average of bilateral difference in hourly day ahead price between Ireland and Great Britain. Grey vertical line shows I-SEM launch. Sources: Authors' analysis; ENTSO-E; SEM-O.

Second, we adopted the methodology proposed by Böckers & Heimeshoff (2014) of testing for an effect on the domestic price of an exogenous reduction in foreign electricity demand due to a national holiday. Results for this regression analysis (see Equation 1) are presented in Table 2, with results shown for our full study period (column 1), the period before market integration (column 2), and the period after integration (column 3). As expected, the exogenous decrease in domestic electricity demand due to national holidays in Ireland decreased Ireland's day ahead price, lending credibility to this approach. In addition, column 1 reveals that the day ahead price in Ireland was lower on national holidays that only occurred in Great Britain, with the absolute magnitude of the effect similar to that of domestic holidays. Interestingly, columns 2 and 3 indicate that this effect stemmed from the period following the launch of I-SEM where the negative effect of British holidays on the Irish price was larger in magnitude than the positive effect of domestic holidays, perhaps due to the fact that Great Britain is a much larger market zone. This represents further evidence of a higher level of market integration between Ireland and Great Britain following the launch of I-SEM.

Table 2: Effect of national holidays on day ahead price in Ireland

	(1)	(2)	(3)
IE holidays	-0.08^{***}	-0.08^{***}	-0.09^{***}
	(0.01)	(0.01)	(0.03)
GB-only holidays	0.08^{***}	0.03	0.15^{**}
	(0.03)	(0.02)	(0.06)
GB-only holidays X peak	-0.003	0.01	-0.02
	(0.06)	(0.05)	(0.14)
Year fixed effects	Yes	Yes	Yes
Calendar month fixed effects	Yes	Yes	Yes
Day of week fixed effects	Yes	Yes	Yes
Hour of day fixed effects	Yes	Yes	Yes
Monthly natural gas price	Yes	Yes	Yes
Observations	52,488	32,736	19,752
Adjusted R^2	0.30	0.38	0.30
Notes:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$
			Column (1): full sample.
			Column (2): before I-SEM.
			Column (3): after I-SEM.

4.3. Why did market integration not have a larger effect?

While the integration of Ireland's Single Electricity Market with the wider European market affected the efficiency of cross-border flows and the extent of market integration with Great Britain, despite theoretical predictions to the contrary we found little evidence of an effect on the level of cross-border flows, the day ahead price or renewable electricity generation. What could explain this? Figure 7 depicts descriptive evidence that offers a clue. Following market integration, the interconnector between Ireland and Great Britain was being utilised at maximum capacity much more frequently than before. This points to transmission congestion that may have acted as a barrier to further increases in cross-border flows, thus preventing price harmonisation. While changes in technical market arrangements due to I-SEM increased the efficiency of electricity trade, insufficient physical transmission infrastructure appears to have constrained any further market integration effects.

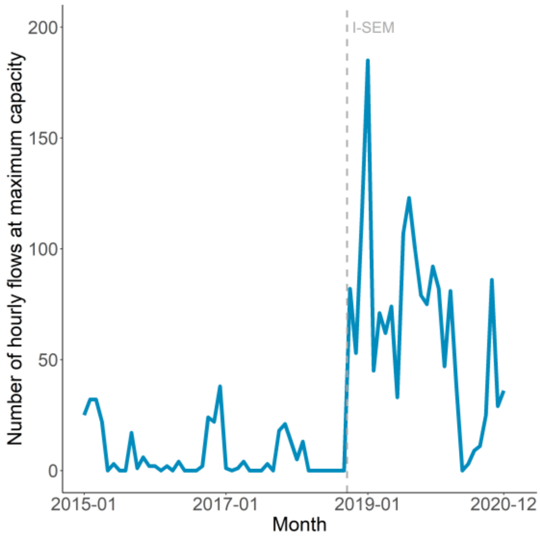


Figure 7: Monthly number of hours when cross-border electricity flows from Great Britain to Ireland were at maximum interconnector capacity, 2015-2020. Grey vertical line shows I-SEM launch. Sources: Authors' analysis; ENTSO-E; SEM-O.

5. Discussion

The integration of Ireland's hitherto isolated Single Electricity Market with Europe's Internal Energy Market in October 2018 offers a compelling case study to empirically test a range of theoretical predictions about electricity market integration. We combined electricity market data from ENTSO-E with legacy data from Ireland's SEM-O to create a comprehensive panel dataset covering the 2015-2020 period and analysed this data using the synthetic control method.

One aspect of the I-SEM market integration was an improvement in technical market arrangements designed to optimise the use of Ireland's interconnectors. We found an immediate negative effect on inefficient electricity flows due to the launch of I-SEM, with electricity flowing efficiently from the lower- to the higher-priced zone much more regularly due to market integration. These results were in line with Montoya et al. (2020) and Newbery et al. (2016).

Contrary to theoretical predictions, and in contrast with the empirical findings of Batalla et al. (2019), we did not find evidence of an increase in electricity imports or exports that could be causally attributed to the launch of I-SEM. Based on this, as theories such as the Law of One Price are predicated on increased trade between markets once they are integrated, it was not surprising that we did not find any effect on Ireland's day ahead wholesale electricity price. Furthermore, unlike Gonzales et al. (2023) who focused on transmission infrastructure expansion, we found no effect on renewable electricity generation due to the technical market integration of Ireland and Europe.

However, similar to Böckers & Heimeshoff (2014), we found that the degree of market integration between Ireland and neighbouring Great Britain was higher after the launch of I-SEM, as exogenous electricity demand reductions in Great Britain due to national holidays reduced the day ahead price in Ireland. This result, coupled with our finding in relation to cross-border flow efficiency, indicate some success in integrating Ireland's Single Electricity Market with the wider European market.

We presented descriptive evidence that Ireland's interconnectors with Great Britain were being utilised at maximum capacity much more frequently in the wake of market integration. This may explain why we found no effect on the level of electricity trade, the wholesale price or renewable electricity generation, as transmission congestion would have prevented further increases in cross-border flows and price harmonisation.

5.1. Policy implications

Efficient use of existing cross-border electricity interconnectors should be a policy goal, and our results show that harmonising the market rules on either side of an interconnector and establishing granular markets can significantly boost cross-border flow efficiency.

The I-SEM case study is also interesting as it represents an integration of technical market arrangements without increasing cross-border transmission capacity. Our findings clearly highlight that while a technical market integration can enhance cross-border flow efficiency and the degree of market integration, a sufficient level of transmission infrastructure is required to realise the full benefits of integration in terms of lower average prices and increased renewable electricity capacity. As transmission infrastructure is unlikely to be optimally provided by the market, there is a role for policy in expanding this infrastructure to reduce transmission congestion and move closer to a fully integrated electricity market.

5.2. Limitations and strengths

The findings of this study should be interpreted in the context of certain limitations. First, as outlined in Appendix A, to furnish our synthetic control analysis with a fully balanced panel, some missing observations had to be imputed, although the percentage of observations in this category was small. Second, while the synthetic control method can effectively mitigate time-invariant omitted variable bias, the possibility of omitted variable bias arising from unobserved factors that vary over time cannot be ruled out.

However, this study can also boast several key strengths. First, the integration of Ireland's previously isolated island electricity market with Europe provided an ideal case study to empirically test a range of theoretical predictions in relation to electricity market integration. Second, by combining ENTSO-E and SEM-O data, we collated a comprehensive panel of high-frequency electricity market data to analyse Ireland's Single Electricity Market before and after market integration with Europe. Third, this data allowed us to apply the synthetic control method, hailed as a major innovation in causal inference, to the question of electricity market integration and contribute to the expanding base of empirical evidence on this topic.

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Disclosure statement

The authors have no competing interests to declare.

Data availability statement

The data that support the findings of this study are available through the ENTSO-E Transparency Platform and the Single Electricity Market Operator (SEM-O).

CRediT authorship contribution statement

Ciarán Mac Domhnaill: Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – reviewing and editing, Visualisation. **Lisa Ryan:** Conceptualisation; Methodology; Data curation; Writing – original draft; Writing – review and editing; Project administration; Funding acquisition. **Ewa Lazarczyk:** Conceptualisation; Methodology; Data curation; Writing – original draft.

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Appendix A: Data

ENTSO-E Transparency Platform data

The bulk of our data was sourced from the ENTSO-E Transparency Platform, which centrally collects and publishes comprehensive data on Europe's wholesale electricity market from Transmission System Operators (TSOs). For all variables, we downloaded hourly data in UTC.

Day ahead price. This is the hourly day ahead price (in nominal currency/MWh) in each bidding zone. We converted any prices that were published in a local currency to EUR using daily exchange rates.

Total load, forecast and actual. TSOs are required to calculate and submit forecast and actual total load for their bidding zone. Actual total load is defined as net generation – exports + imports – absorbed energy, and is calculated as an average of real-time load values for the respective period. The day ahead forecast of this load is estimated on historic load profiles for similar days, accounting for factors such as weather, climate and socioeconomic variables. It is provided for information purposes and must be published before the closure of the day ahead market.

Generation forecasts for wind and solar. For each bidding zone and market time unit, current, day ahead and intraday forecasts for onshore wind, offshore wind and solar power generation are published for zones in EU Member States with more than 1 per cent feed-in, or zones with more than 5 per cent feed-in, of wind or solar per year. For our analysis, we employed day ahead generation forecasts, which is the most recent forecast as of 18:00 Brussels time the day before delivery.

Actual generation per production type. Data on actual aggregated net generation output (in MW) per market time unit and per production type is published within an hour of the operational period. Actual generation is calculated as the mean of all available instantaneous net generation output values during the respective period. We used this data to calculate renewable electricity generation and hydropower generation. As with forecast data, actual generation of wind and solar is only published for zones in EU Member States with more than 1 per cent feed-in, or zones with more than 5 per cent feed-in, of wind or solar per year.

Cross-border physical flows. Physical flows between bidding zones are published for each market time unit. These are defined as the measured real flow of energy (in MW) between neighbouring bidding zones.

Outages. Planned or forced outages in the electricity grid are reported and published. We accessed data on planned and forced unavailability of generation units, including their remaining available capacity during the outage.

Single Electricity Market Operator (SEM-O) data

As Ireland's Single Electricity Market was not part of the European market until I-SEM, day ahead price data for the Irish bidding zone did not exist before October 2018. Prior to this, the equivalent wholesale price in the Single Electricity Market was known as the ex-post system marginal price, calculated four days after trading day. We sourced legacy half-hourly data on the ex-post (EP2) system marginal price (in nominal EUR/MWh) from the SEM-O. We aggregated this data to the hourly level by taking hourly means, and where SEM-O data had been adjusted for daylight saving time, we converted times back to UTC for consistency with our ENTSO-E panel.

Population data

For the calculation of per capita variables, population data was sourced mainly from the World Data Bank. This sufficed for all bidding zones that covered a whole country. However, more disaggregated data was required where countries contained multiple zones. We used Office for National Statistics (ONS) data to separate the population of Northern Ireland from Great Britain, while for Ireland, we added the Northern Irish population to that of the Republic of Ireland to derive the all-island population of the Single Electricity Market. For Sweden, Norway and Denmark, we relied on the regional population data from the Swedish Statistical Database, Statistics Norway and Statistics Denmark respectively. As statistical regions did not align perfectly with bidding zone boundaries, we assigned regions to bidding zones as outlined in Table A1 based on their geographic locations.

Table A1: Statistical regions assigned to bidding zones for Sweden, Norway and Denmark

Bidding zone	Statistical regions
SE1	Norrbotten, Vasterbotten
SE2	Jamtland, Vasternorrland
SE3	Gavleborg, Dalarna, Vastmanland, Orebro, Vastra Gotaland, Varmland, Jonkoping, Sodermanland, Uppsala, Stockholm
SE4	Halland, Skane, Blekinge, Gotland, Kalmar, Kronoberg, Ostergotland
NO1	Ostfold, Akershus, Oslo, Innlandet, Buskerud
NO2	Vestfold, Telemark, Agder
NO3	More og Romsdal, Trondelag
NO4	Nordland, Troms-Romsa-Tromssa, Finnmark-Finnmarku-Finmarkku
NO5	Rogaland, Vestland
DK1	Syddanmark, Midtjylland, Nordtjylland
DK2	Sjaelland

Donor pool

In the synthetic control method, the synthetic control group is constructed as a weighted average of units in the 'donor pool'. Therefore, it is important to be transparent about what countries were in the donor pool. Our most basic criteria for entry into the pool was that the country should also be part of the European wholesale electricity market to some extent.

In 2014, the Single Day Ahead Coupling (SDAC) mechanism was launched among 17 countries: Belgium, Denmark, Estonia, Finland, France, Germany, Austria, Great Britain, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Sweden, Portugal and Spain. Separately, Romania, Czechia, Slovakia and Hungary coupled their day ahead markets to create the 4M Market Coupling (4MMC) group.

Our study period then ran from 2015 to 2020. In February 2015, Italy and Slovenia coupled with SDAC, followed by Croatia in June 2018 and Ireland (our treated unit) in October 2018.

October 2018 also saw the splitting of Germany and Austria into two separate bidding zones within the integrated market. Greece coupled with SDAC in December 2020.

Following our study period, in 2021, Bulgaria and the 4MMC group all coupled with SDAC. As part of the UK's exit from the EU Single Market and Customs Union in January 2021, the Great Britain bidding zone exited SDAC in an unprecedented reversal of electricity market coupling.

Subject to data availability, we considered most of the original 17 SDAC countries and the 4MMC countries as possible donor pool candidates, although we excluded Germany, Austria and Luxembourg due to the splitting of the Germany-Austria bidding zone (Luxembourg is included in the Germany bidding zone) as this represented another possible policy treatment during our study period. This excluded Italy, Slovenia and Croatia as these also coupled with SDAC during our study period and as such could not be considered 'control' cases. As the only country with physical interconnections with Ireland during the study period, we also excluded Great Britain from the donor pool to minimise the risk of potential spillover effects on the synthetic control group. Finally, Poland had to be dropped from the donor pool due to a high level of missing day ahead price data.

Therefore, the countries in our donor pool were: Belgium, Denmark (2 zones), Estonia, Finland, France, Latvia, Lithuania, Netherlands, Norway (5 zones), Sweden (4 zones), Portugal, Spain, Czechia, Slovakia and Hungary.

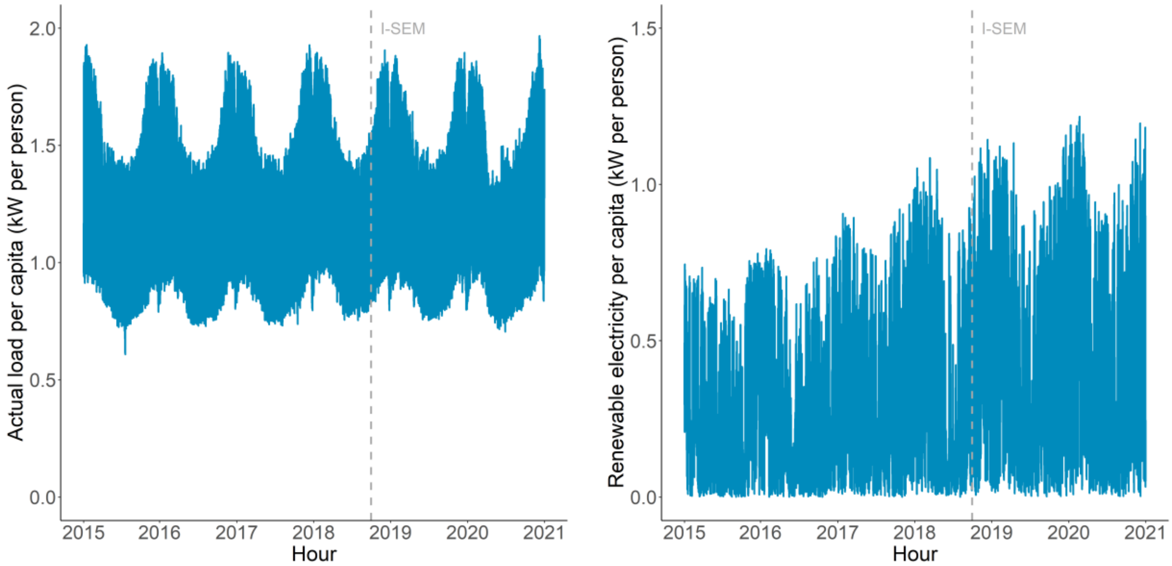
Missing observations

The synthetic control method requires a panel dataset that is fully balanced. Therefore, prior to aggregating the data to the monthly level, we took several steps to deal with missing observations that preserved as many units as possible in the donor pool. However, the extent of missing day ahead price observations was simply too great to include Poland.

First, some data was missing for forecast or actual load or renewable generation. Where possible, we set the missing actual value equal to the non-missing forecast value, or vice versa. Second, for remaining missing values in price or load variables, we set the value equal to the bidding zone value for that same hour during the previous week. This only affected 0.02 per cent of day ahead price and 0.01 per cent of load observations. Third, for remaining missing values in renewable generation and hydropower variables, we set the value equal to the most recent non-missing value. This only affected a very small number of observations, ranging from 0.08 per cent for hydropower generation to 0.001 per cent for offshore wind generation.

Appendix B: Additional tables and figures

Figure B1 displays additional hourly data for Ireland's Single Electricity Market during the study period. As expected, in panel (a), electricity demand continued to follow a distinct daily and seasonal pattern after the launch of I-SEM. Meanwhile, on the supply side, the steady increase in renewable electricity generation during this period, predominantly from onshore wind, is charted in panel (b).



(a) Actual electricity load per capita. (b) Renewable electricity generation per capita.

Figure B1: Hourly market data, Ireland Single Electricity Market 2015-2020. Grey vertical line shows I-SEM launch. Source: Author's analysis; ENTSO-E.

As natural gas is largely traded via international trading hubs such as the Title Transfer Facility in the Netherlands, the wholesale price of natural gas varies over time rather than between electricity market bidding zones. Therefore, the wholesale gas price faced by electricity generators can be treated as a time fixed effect. Figure B2 supports this approach, as it depicts estimated month fixed effects in a monthly panel regression of day ahead prices (Equation 1 in the paper) as largely tracking the global price of natural gas in the EU. Based on this, for our synthetic control method analysis of the day ahead price and its volatility, we first ran fixed effects regressions including only month fixed effects, and employed the residuals of these regressions as the outcome variable in the synthetic control analysis. Essentially, this applied the synthetic control method only to the remaining variation in day ahead prices and price volatility that could not be explained by common time-varying factors such as the global wholesale price for natural gas.

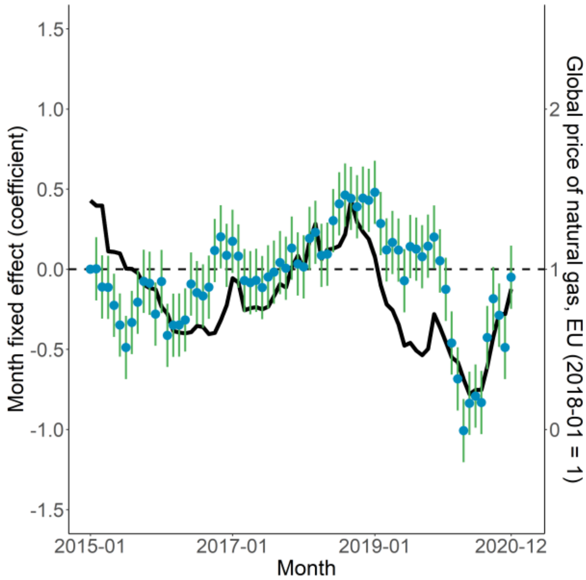


Figure B2: Month fixed effects (blue points, left-hand y-axis) and 95 per cent confidence intervals from panel regression of day ahead prices and global price of natural gas (black solid line, right-hand y-axis), Europe 2015-2020. Sources: Authors' analysis; ENTSO-E; SEM-O.

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