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The effect of flow-based market coupling on cross-border exchange volumes and price convergence in Central Western European electricity markets

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ABSTRACT

Since 2015 available cross-border transmission capacity is determined using flow-based market coupling (FBMC) in the day-ahead electricity markets of Central Western Europe. This paper empirically estimates the effect of introducing FBMC on day-ahead electricity price convergence and cross-border exchange volumes. In the month following the introduction of FBMC, hourly cross-border exchange volumes increased by 1,700 MWh/h, while prices between countries converged by 10.4 €/MWh. Since then, observed cross-border exchange volumes decreased to 400 MWh/h below their levels before the introduction of FBMC by the end of 2017. However, when controlling for changing market conditions in the years following the introduction of FBMC, we find that FBMC still has a persistent positive effect of around 1,150 MWh/h on hourly cross-border exchange volumes and of 2 €/MWh on price convergence. Finally, we provide suggestive evidence that decreased commercial transmission capacity on critical branches might have contributed to the decline of the benefits over time. This paper is useful for policymakers, regulators, TSOs, and other stakeholders in light of the extension of FBMC to other regions as it is the target methodology for coupling market zones in the European single electricity market.

1. Introduction

Coupling electricity markets increases economic efficiency, as it allows for more trade from low-cost regions to high-cost regions. However, the commercial exchange of electricity between market zones is limited by the transmission capacity that is made available to the market, i.e., the cross-border transmission capacity allocation (European Commission, 2015). In the European single electricity market, the target method to allocate cross-border capacities is flow-based market coupling (FBMC). It has been operational in the day-ahead electricity markets of Central Western Europe (CWE)[1] since May 2015, replacing the Available Transfer Capacity (ATC) method.

FBMC is considered to lead to more commercial exchanges between zones than ATC, as it uses a more detailed representation of the electricity network and the flows on the network. This makes it possible to make a better trade-off between real-time reliability of the system (which typically calls for less commercial exchanges) and economic efficiency (which requires more commercial exchanges) (Ovaere and Proost, 2018).

Before going live, FBMC was tested in parallel off-line runs (Amprion et al., 2015) and its results were compared to the actual cross-border exchanges and prices under ATC. During these runs the FBMC method increased cross-border exchanges and price convergence, resulting in a M€95 increase in economic surplus for 2013 (Amprion et al., 2015). Since its introduction in CWE in 2015, a number of European regulators and stakeholders claim that the gains are below expectations. For example, CREG (2017) observes that total exchanges in the CWE region have decreased following the introduction of FBMC, while ACER (2020) states that too little cross-border transmission capacity is allocated to the market. However, all of these papers only analyze the observed exchanges and price convergence, while the power system has drastically changed since the introduction of FBMC, e.g., increased solar and wind generation, exceptionally long outages of

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[1] CWE consists of Belgium, France, Germany/Austria/Luxembourg, and the Netherlands (ACM et al., 2015). As Germany, Austria, and Luxembourg are one price zone in our sample, we refer to this zone as 'Germany' (DE) in the remainder of this paper.

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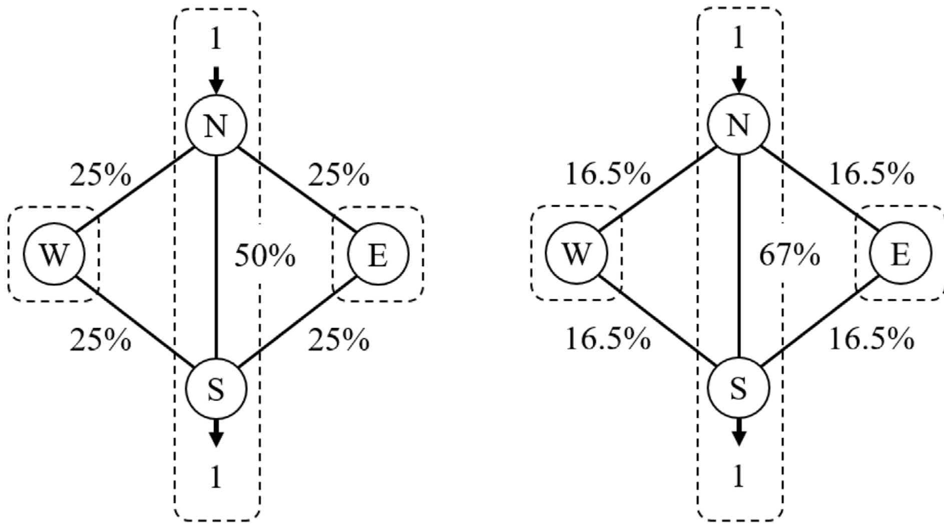


(a) Equal impedance for all lines. (b) Impedance N-S line half of others.

Fig. 1. Physical flows in 4-node network (solid circles) and 3 market zones (dashed lines).

large (nuclear) power plants, changes in load patterns, and changing coal, gas and carbon prices. Only by controlling for these changes in the market conditions, one can isolate the true impact of FBMC.

In this paper, we aim to answer the question of whether FBMC delivered on its promises of increased cross-border trade and increased price convergence in the day-ahead markets of CWE. Using five years of hourly electricity market data in each CWE country, we empirically estimate the short- and long-term effect of the introduction of FBMC. We find that observed cross-border exchanges in CWE immediately jumped up with around 1700 MWh/h right after the introduction of FBMC, but then fully disappeared within a year and leveled off at around 400 MWh/h lower than before the introduction of FBMC. However, if we control for changing market conditions, we find that by the end of 2017, around 1150 MWh/h or 70% of the initial additional cross-border exchanges from FBMC still remain. We provide suggestive evidence that decreased commercial transmission capacity on critical branches might have contributed to the initial decline of the benefits over time. Similarly, prices differences between the CWE countries decreased by a total of 10.4 €/MWh immediately after the introduction of FBMC. By the end of 2017, price convergence (both observed and after controlling for market conditions) had decreased again, but was still higher than before the introduction of FBMC. We do not consider data after 2017 because of multiple exogenous shocks in the data (German–Austrian market zone split, introduction of intra-CWE transmission lines,..) and to preserve symmetry (around 2.5 years before and after the introduction of FBMC).

As FBMC is the target market-coupling method for the European single electricity market (European Commission, 2015) and will be extended from CWE to the CORE region[2] in 2022 (ACER, 2019; Vajdić and Kelava, 2020), this analysis is useful for policymakers, regulators, TSOs and market participants. In addition, our paper performs the first empirical analysis estimating the impact of the introduction of FBMC on cross-border exchange volumes and price convergence in CWE that explicitly accounts for the changing market conditions. Therefore it contributes to the ongoing discussion on whether and what type of regulatory intervention in FBMC is desirable. Finally, the methodology in this paper could be applied to a wide variety of policy effects, in and beyond the energy sector.

The paper continues as follows. Section 2 explains the main principles of FBMC. Section 3 outlines the used methodology and data. Section 4 presents results. Next, Section 5 discusses the implications of our results for the further extension of FBMC throughout Europe. Finally, Section 6 concludes.

2. Physical versus commercial transmission capacity

Zonal market coupling plays a key role in the European Union's goal of a single, interconnected and EU-wide electricity market as it fosters emission reductions and more competition, hence, more market surplus, lower prices, and improved reliability (European Commission, 2021). However, exchange between and within market zones is limited by the physical capacity of the transmission grid. Electricity does not flow point-to-point from producer to consumer but flows through the grid according to Kirchhoff's laws. As a result, electric power spreads across all parallel paths between the point of injection (e.g. a generator) and the point of withdrawal (i.e., the consumer), and the resulting flow on a parallel path is inversely-proportional to the impedances of the parallel paths (Weibelzahl, 2017).

Kirchhoff's laws are illustrated by means of a simple network in Fig. 1, consisting of 4 nodes (North, East, South, West) grouped in 3 market zones and connected by 5 identical lines. A lossless DC power flow analysis[3] shows that, for an injection in node North and a withdrawal in node South, 25% flows through the eastern path, 50% through the central path and 25% through the western path (Fig. 1(a)). If North and South are in the same market zone, an intra-zonal commercial transaction between these nodes will not only flow between the two nodes in the market zone but also lead to physical flows through the neighboring market zones West and East. These flows are referred to as loop flows. As they result from intra-zonal transactions, they are not "seen" by the market. If the impedance of the central line (North–South) is only half of the other lines, the flow through the central path increases to 67% and decreases to 16.5% in the other paths (Fig. 1(b)).

Because of this disconnect between commercial exchange and physical flows, not all physical transmission capacity can be used for trading

[2] The CORE region consists of Austria, Belgium, Croatia, Czechia, France, Germany, Hungary, Luxembourg, the Netherlands, Poland, Romania, Slovakia, and Slovenia.

[3] A lossless DC power flow analysis is a linear approximation of Kirchoff's laws, assuming that (i) voltage angle differences are small between neighboring nodes, (ii) voltage is equal for all nodes, and (iii) line resistances are small compared to line reactances (Van den Bergh et al., 2014).

electricity (Schönheit et al., 2022). The commercial transmission capacity, used for trade, is lower than the actual physical capacity, to, i.a., anticipate loop flows. It is the role of the Transmission System Operators (TSOs) to determine the available commercial transmission capacity – so-called cross-border capacity allocation (European Commission, 2015; CREG, 2017). Currently, two different cross-border capacity allocation mechanisms are used in Europe: Flow-Based Market Coupling (FBMC) and Available Transfer Capacity (ATC). In the FBMC method, the day-ahead market clearing accounts for the physical characteristics of the grid (i.e., Kirchhoff's laws) - although less detailed than in nodal pricing, which accounts for the full network. The ATC method, on the other hand, uses static point-to-point flows between generators and consumers. Because the FBMC method is a more accurate representation of grid limits and loop flows in the market clearing algorithm, it can be less conservative than ATC and as such allow for greater trading domains (Kristiansen, 2020).

The reduction of a full description of the physical grid (physical capacity) – like in markets with nodal pricing – to a simplified market model (commercial capacity) consists of two steps. In the first step, a simplified network model is derived from the physical grid. ATC and FBMC are based on a different network model. In ATC, power flows point-to-point, while in FBMC the physical nature of the grid is (partly) taken into account. Specifically, under FBMC, TSOs determine a set of critical transmission lines (both intra-zonal and inter-zonal) on which the expected flow is calculated. In the second step, the commercial transmission capacity on critical transmission lines is calculated by reducing the physical capacity in two ways: (i) a loop flow margin to account for flows through the grid that are not "seen" by the market and (ii) a safety margin to deal with unforeseen events such as unplanned outages of transmission lines or power plants. The resulting commercial transmission capacity, also referred to as the Remaining Available Margin (RAM) of a transmission line, is the maximum allowed flow on a specific line because of commercial exchange in the day-ahead market. A lower commercial transmission capacity reduces the possibility for cross-border trade by decreasing the so-called flow-based domain of feasible market-clearing outcomes (Wyrwoll et al., 2018; Schönheit et al., 2020b; Van den Bergh et al., 2016).[4] The market clearing procedure ultimately results in a dispatch of generators. This comes with a net export position (NEP) of each zone.

3. Data and methodology

In this section we use 2013–2017 data to estimate the short- and long-term effect of the introduction of flow-based market coupling in Central Western Europe on May 20, 2015. First, we apply the regression discontinuity in time (RDiT) framework, which allows us to precisely estimate the short-term effect of the introduction of the FBMC methodology on cross-border exchanges and price differences between the CWE countries. RDiT is the preferred method to estimate the short-term effect of a change when time is the running variable and the treatment begins at a particular threshold in time (Hausman and Rapson, 2018), like in this case with the introduction of FBMC. Papers using RDiT span fields that include public economics, industrial organization, environmental economics, marketing, and international trade (Auffhammer and Kellogg, 2011; Chen and Whalley, 2012; Davis, 2008). To our knowledge, this is the first paper applying RDiT to electricity markets and to electricity transmission in specific. Next, we estimate the long-term effect of FBMC in a time-series study with a rich set of controls: commodity prices, hourly day-ahead solar and wind generation, hourly generation and generation unavailability of non-intermittent technologies, day-ahead load in CWE, temperatures in CWE, and commercial exchanges with non-CWE countries.

[4] A full description of the FBMC method is beyond the scope of this paper but can be found in Schönheit et al. (2021).

3.1. Data

Our first variable of interest is the total day-ahead cross-border exchange by the four CWE countries at each time t in our sample. By definition, the total cross-border exchange X_t is half of the sum of the absolute net export position (NEP) of each CWE country[5]:

$$X_t = 0.5 \left(|NEP_{DE,t}| + |NEP_{NL,t}| + |NEP_{BE,t}| + |NEP_{FR,t}| \right) \tag{1}$$

The NEP of a country equals exports minus imports, such that a positive NEP equals net exports and a negative NEP net imports into a country. In the remainder of this paper we generally focus on the absolute value of NEP, meaning that an increasing value might indicate higher imports as well as higher exports. In our sample period, Belgium and the Netherlands are almost always importing, Germany almost always exports, and France imports a bit more than it exports, as shown in Table 1.

Our second variable of interest is the total hourly weighted day-ahead price difference (ΔP_t). We define ΔP_t as the sum of the absolute values of the hourly price differences between the CWE countries, weighted by the load in the considered countries. The weights reflect that certain price differences (e.g., Germany–France compared to Belgium-The Netherlands) may have a bigger impact on market surplus.[6] ΔP_t reads as follows:

$$\begin{aligned}\Delta P_t = \Big[& |p_{NL,t} - p_{BE,t}| \times (load_{t,NL} + load_{t,BE}) \\ & + |p_{BE,t} - p_{FR,t}| \times (load_{t,BE} + load_{t,FR}) \\ & + |p_{NL,t} - p_{DE,t}| \times (load_{t,NL} + load_{t,DE}) \\ & + |p_{FR,t} - p_{DE,t}| \times (load_{t,FR} + load_{t,DE}) \\ & + |p_{DE,t} - p_{BE,t}| \times (load_{t,DE} + load_{t,BE}) \\ & + |p_{FR,t} - p_{NL,t}| \times (load_{t,FR} + load_{t,NL}) \Big] \\ & \times \frac{0.5}{load_{t,BE} + load_{t,DE} + load_{t,FR} + load_{t,NL}}\end{aligned} \tag{2}$$

When there is full price convergence, prices in all CWE countries are identical and ΔP_t equals zero. In this case, the economic potential of cross-border trade between those countries is fully used. On the other hand, if there exists a price difference among two countries, cross-border trade between those countries is limited by the transmission grid.

Table 1 shows the mean and standard deviation of the dependent variables, total cross-border exchanges (X_t) and price differences (ΔP_t), as well as the underlying prices and exchanges in each CWE country, before (January 1, 2015–May 19, 2015) and after (May 20, 2015–December 31, 2017) the introduction of FBMC. The import and export variables represent the average value during hours of import and export, respectively. The last column presents the difference between the means in our sample before and after the introduction of FBMC. It shows that some of the variables increased and others decreased in the period after the introduction of FBMC, but all changes are highly significant. Observed cross-border exchanges X_t were on average 440 MW lower in the years after the introduction of FBMC than in the five months before.[7] Zooming in on the specific countries, the net exchange position of Belgium and Germany decreased considerably after the introduction of FBMC, mainly because of lower imports in

[5] This includes cross-border exchange volumes within the CWE region, but also half of the cross-border exchange volumes from CWE countries to neighboring non-CWE countries or vice versa.

[6] The main results do not change much when ΔP_t is the unweighted price difference between the CWE countries.

[7] Compared to the full 2.5-years pre-period, the difference is 475 MW.

Table 1
Summary statistics. Mean and standard deviation of the dependent variables, total cross-border exchanges (X_t) and price differences (ΔP_t), as well as the underlying prices and exchanges in each CWE country, before (January 1, 2015–May 19, 2015) and after (May 20, 2015–December 31, 2017) the introduction of FBMC. The last column presents the difference between the means in our sample before and after the introduction of FBMC. The import and export variables represent the average value during hours of import and export, respectively. All differences are highly significant (at p = 0.001). Both hourly day-ahead electricity prices and NEPs of all four CWE countries were obtained from the Belgian regulator (CREG) for 2013–2017.

Variable	Pre-FBMC		Post-FBMC		Difference
	Mean	Std. dev.	Mean	Std. dev.	
Exchange volumes [MWh/h]:					
X_t	4317	(818)	3877	(1511)	−440
$\|NEP_{t,BE}\|$	2353	(785)	1342	(958)	−1011
$\|NEP_{t,DE}\|$	3740	(1426)	2824	(1701)	−916
$\|NEP_{t,FR}\|$	1343	(1021)	2174	(1646)	831
$\|NEP_{t,NL}\|$	1198	(604)	1415	(1085)	217
$imports_{t,BE}$	2252	(906)	1235	(1043)	−1017
$imports_{t,DE}$	1	(26)	113	(461)	112
$imports_{t,FR}$	785	(945)	1332	(1730)	547
$imports_{t,NL}$	1095	(676)	1197	(1207)	102
$exports_{t,BE}$	1	(22)	107	(305)	106
$exports_{t,DE}$	3579	(1589)	2711	(1815)	−868
$exports_{t,FR}$	500	(982)	842	(1400)	342
$exports_{t,NL}$	52	(255)	218	(491)	166
Price differences [€/MWh]:					
ΔP_t	14.3	(10.7)	10.8	(18.0)	−3.5
$\Delta P_{t,BE-DE}$	10.7	(11.7)	9.8	(19.0)	−0.9
$\Delta P_{t,BE-FR}$	3.9	(9.4)	6.7	(17.4)	2.8
$\Delta P_{t,BE-NL}$	5.1	(10.4)	4.1	(12.0)	−1.0
$\Delta P_{t,DE-FR}$	10.7	(10.6)	8.5	(16.3)	−2.2
$\Delta P_{t,DE-NL}$	11.8	(10.9)	5.6	(9.9)	−6
$\Delta P_{t,FR-NL}$	8.6	(10.4)	7.4	(14.2)	−1.2
$P_{t,BE}$	46.1	(13.9)	41.3	(23.5)	−4.8
$P_{t,DE}$	30.5	(13.6)	31.8	(14.8)	1.3
$P_{t,FR}$	41.0	(13.5)	39.9	(20.9)	−1.1
$P_{t,NL}$	42.3	(10.3)	36.5	(12.3)	−5.8
Observations	3215		22,942		26,157

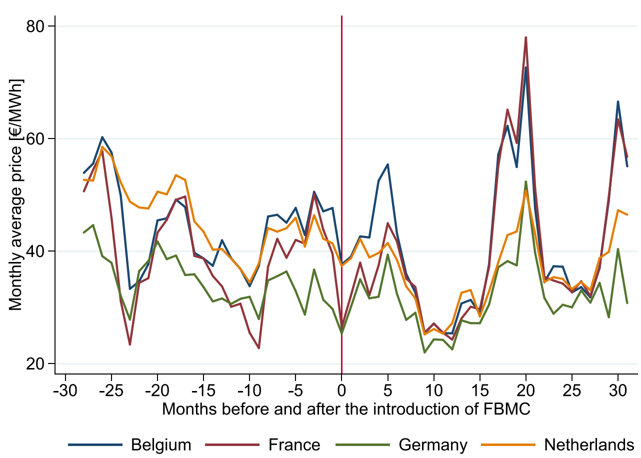


Fig. 2. Monthly average price developments in each CWE country.
Source: ENTSO-E (2019).

Belgium and lower exports in Germany. On the contrary, NEP increased in France and the Netherlands, because of both higher imports and higher exports. Our measure of weighted price differences decreased on average by 3.5 €/MWh. Prices converged on each border after the introduction of FBMC, except between France and Belgium. Wholesale day-ahead prices fell on average in all countries except in Germany, with the largest decrease in The Netherlands (5.8 €/MWh). Fig. 2 shows the monthly average price developments in each CWE country.

We compile hourly day-ahead wind and solar generation, hourly day-ahead generation by non-intermittent technologies, hourly amount of non-intermittent generation capacity that is unavailable by technology, hourly commercial exchanges with non-CWE countries, and day-ahead total load[8] from the ENTSO-E Transparency Platform (ENTSO-E, 2019) for each CWE country. These control variables for the long-term analysis are only available since 2015. Additionally, daily gas (TTF hub, €/MWh), coal (API2 hub, €/ton, converting $ to € using the daily exchange rate) and European Emission Allowance prices (€/tonCO_2) are downloaded from the Thompson Reuters Eikon platform. Finally, hourly temperatures for each CWE country are downloaded from Open Power System Data platform (2022).

All differences between the mean value of a variable before and after the introduction of FBMC are highly significant (at p=0.001), except coal generation in the Netherlands. As these changing market conditions have an effect on both cross-border exchange volumes (X_t) and price differences (ΔP_t), they need to be included as control variables to correctly estimate the long-term impact of the introduction of FBMC on X_t and ΔP_t.

The same summary statistics are presented in Table 2 for the control variables used in our long-term analysis. This table shows that market conditions changed considerably after the introduction of FBMC. Load decreased in all countries except The Netherlands, with the largest absolute decrease in France (7120 MWh/h). Electricity generation from renewable energy sources rose in almost all CWE countries, with the highest increase in Germany (+954 MWh/h wind power and +217 MWh/h solar power) – four times more than the second largest increase, which is realized in The Netherlands (+214 MWh/h wind power and +76 MWh/h solar power). Electricity generation from non-intermittent technologies (gas, coal and nuclear) decreased in the CWE region by 5141 MWh/h on average, mainly driven by a decrease

[8] Total load is the sum of power generated by plants on both transmission and distribution networks, subtracting the balance of exchanges on interconnections between neighboring bidding zones and the power absorbed by energy storage resources (ENTSO-E, 2021b).

Table 2
Mean and standard deviation of the control variables before (1 January 2015–19 May 2015) and after (20 May 2015–31 December 2017) the introduction of FBMC, as well as the difference between the means before and after the introduction of FBMC. All differences are highly significant (at p = 0.001), except coal generation in the Netherlands ($coal_{t,NL}$).

Variable	Pre-FBMC		Post-FBMC		Difference
	Mean	Std. dev.	Mean	Std. dev.	
Electricity demand [MWh/h]:					
$load_{t,BE}$	10,553	(1317)	9779	(1357)	−774
$load_{t,DE}$	55,833	(9210)	54,993	(9689)	−840
$load_{t,FR}$	60,472	(11,985)	53,351	(11,502)	−7121
$load_{t,NL}$	12,398	(2545)	13,539	(2322)	1141
Renewable generation [MWh/h]:					
$wind_{t,BE}$	610	(483)	575	(486)	−35
$wind_{t,DE}$	8752	(6978)	9706	(7728)	954
$wind_{t,FR}$	2383	(1620)	2322	(1633)	−61
$wind_{t,NL}$	711	(600)	925	(756)	214
$solar_{t,BE}$	317	(519)	332	(509)	15
$solar_{t,DE}$	3654	(5888)	4113	(6222)	459
$solar_{t,FR}$	726	(1037)	943	(1291)	217
$solar_{t,NL}$	102	(170)	178	(283)	76
Conventional generation [MWh/h]:					
$gas_{t,BE}$	2614	(915)	2432	(822)	−182
$gas_{t,DE}$	1034	(723)	1751	(1299)	716
$gas_{t,FR}$	3163	(2070)	3889	(2538)	726
$gas_{t,NL}$	2357	(1737)	3178	(1859)	821
$coal_{t,BE}$	249	(121)	71	(150)	−178
$coal_{t,DE}$	15,316	(2610)	14,948	(2234)	−368
$coal_{t,FR}$	1500	(1102)	891	(781)	−610
$coal_{t,NL}$	373	(128)	57	(140)	−316
$nuclear_{t,BE}$	3135	(639)	4180	(1200)	1,045
$nuclear_{t,DE}$	10,232	(933)	8822	(1522)	−1410
$nuclear_{t,FR}$	50,009	(7286)	43,940	(6208)	−6069
$nuclear_{t,NL}$	510	(132)	453	(194)	−57
Unavailable generation capacity [MW]: (most important variables)					
$unavnuclear_{t,BE}$	2462	(539)	1715	(1098)	−747
$unavcoal_{t,DE}$	5981	(2330)	6461	(3275)	480
$unavgas_{t,DE}$	2566	(1291)	3088	(1549)	522
$unavnuclear_{t,FR}$	10,699	(6029)	16,901	(5757)	6202
Commodity prices:					
Coal p_{coal} [€/ton]	48.77	(2.93)	54.41	(13.45)	5.64
Gas p_{gas} [€/MWh]	21.4	(1.3)	16.4	(2.9)	−5
Carbon price p_{co_2} [€/ton]	7.1	(0.3)	6.2	(1.4)	−0.9
Temperature [degree C]:					
$temperature_{t,BE}$	8.81	(6.61)	11.37	(6.67)	−2.56
$temperature_{t,DE}$	8.00	(7.69)	10.73	(8.00)	−2.73
$temperature_{t,FR}$	10.73	(6.67)	13.24	(6.89)	2.51
$temperature_{t,NL}$	8.81	(6.61)	11.37	(6.67)	−2.56
Exchanges with non-CWE countries [MWh/h]: (most important variables)					
$nonCWE_{CH-DE}$	293.12	(826.80)	162.62	(522.40)	−130.5
$nonCWE_{CH-FR}$	1200.74	(1057.52)	881.84	(861.72)	−318.9
$nonCWE_{FR-CH}$	3007.45	(562.96)	2197.53	(1045.24)	−809.9
$nonCWE_{FR-ES}$	735.85	(541.50)	1615.69	(1016.03)	879.8
$nonCWE_{FR-IT}$	2367.64	(952.23)	2117.63	(967.39)	−250.0
$nonCWE_{UK-FR}$	201.40	(517.75)	335.84	(561.08)	134.4
$nonCWE_{FR-UK}$	1841.73	(341.18)	1492.03	(716.56)	−349.7
$nonCWE_{DK-DE}$	585.00	(542.91)	572.49	(483.73)	−12.51
$nonCWE_{CZ-DE}$	1925.02	(596.06)	912.92	(704.36)	−1012.1
Observations	3359		22,945		26,304

in nuclear power generation in France of 6069 MWh/h. Generation from coal power plants decreased in all CWE countries. Only gas power generation in Germany, France and The Netherlands, and nuclear power generation in Belgium and The Netherlands increased after the introduction of FBMC. Table 2 also presents the most important unavailabilities (but note that we use data on unavailability of all conventional technologies in each CWE country) and shows, i.a., that the unavailability of nuclear power in Belgium as well as coal power and gas power in Germany decreased, providing more options to the market to cover the demand for electricity. However, at the same time, a strong increase in the unavailability of nuclear power in France of 6202 MW is observed. Next, the gas price dropped on average by 5 €/MWh, while the coal price increased, meaning that the marginal cost of gas power decreased relative to the cost of coal power (even when including the slightly decreasing carbon cost). Finally, total commercial exchanges with non-CWE-countries decrease on average. Specifically, exchanges from France to Switzerland (−809.9 MWh/h) and from Czechia to Germany (−1012.1 MWh/h) drop the most. The highest increase in exchanges is observed between France and Spain (+879.8 MWh/h), because of a completed HVDC line in September 2015 (ENTSO-E, 2021a).

3.2. Regression discontinuity in time: short-term effect

We measure the short-term impact of the introduction of FBMC on cross-border exchanges (X_t) and price differences (ΔP_t) using Re-

Table 3
Three specifications to estimate the short-term effect of FBMC on X_t, together with the treatment effect. To estimate the effect on price convergence, the dependent variable is replaced by ΔP.

	Pre-FBMC	Post-FBMC	Treatment effect $\beta_{FBMC,X}$
(1)	$X_{t,pre} = \alpha_0 + \epsilon_t$	$X_{t,post} = \alpha_1 + \alpha_0 + \epsilon_t$	α_1
(2)	$X_{t,pre} = \alpha_{1,pre}\, t + \alpha_{0,pre} + \epsilon_t$	$X_{t,post} = \alpha_{1,post}\, t + \alpha_{0,post} + \epsilon_t$	$\alpha_{0,post} - \alpha_{0,pre}$
(3)	$\overline{X}_{t,pre} = \alpha_{1,pre}\, t + \alpha_{0,pre} + \epsilon_t$	$\overline{X}_{t,post} = \alpha_{1,post}\, t + \alpha_{0,post} + \epsilon_t$	$\alpha_{0,post} - \alpha_{0,pre}$

gression Discontinuity in Time (RDiT). RDiT is a quasi-experimental method that estimates the sudden change of a variable of interest around the moment of a policy introduction. Following (Hausman and Rapson, 2018) and Gelmans and Imbens (2019), we use three different specifications to estimate the short-term effect of FBMC: a simple pre-post comparison of the mean (Specification (1) in Table 3), a local linear estimation (Specification (2) in Table 3), and a two-step augmented local-linear estimation (Specification (3) in Table 3).

Table 3 presents the three specifications to estimate the short-term effect of FBMC, together with the treatment effect. X_t is the cross-border exchange at time t, while $\overline{X}_t$ is the cross-border exchange while controlling for time-fixed effects. To estimate the effect on price convergence, the dependent variable is replaced by ΔP.

The specifications are estimated on a symmetric sample of 60 days around the threshold (t=0), i.e. 720 h of observations on either side, following (Hausman and Rapson, 2018). The short-term effect under these specifications is thus compared to the 30-day pre-sample period. The first specification estimates the effect of FBMC $\beta_{FBMC,X} = \alpha_1$ as the difference in means before and after the introduction. In the second specification, we run standard linear regressions on each side of the threshold: pre = $t \in [-720, -1]$ and post = $t \in [0, 719]$. The treatment effect on cross-border exchanges X under the second and third specification is calculated as $\beta_{FBMC,X} = \alpha_{0,post} - \alpha_{0,pre}$. The third specification is conceptually similar to the second, but the dependent variable $\overline{X}_t$ has been controlled for time-fixed effects (month-of-year, hour-of-day and day-of-week) to eliminate seasonality effects, estimated on the full pre-FBMC sample.[9] While the first specification focuses on the treatment effect in the full 60-day bandwidth, the second and third specification focus more on the value of the regression function right at the discontinuity (Lee and Lemieux, 2010).

The RDiT results show the observed changes in prices and exchanges immediately after the introduction of FBMC. The identifying assumption of RDiT is that all confounding variables vary smoothly around the considered threshold to accurately estimate the treatment effect (Hausman and Rapson, 2018). There are no clear criteria in statistical theory on what can be described as "smoothly varying", but Appendix A shows that most confounding variables do not change much within the 60-day bandwidth around the threshold. However, some variables – like nuclear generation in France, nuclear generation in Belgium, or wind generation in Germany – do change by up to 1400 MWh/h, even in this short time period around the threshold. In the long term, these confounding variables change even more (e.g., French nuclear generation decreases with more than 6000 MWh/h), as shown in Table 2). In the next section we therefore control for these confounding variables in a time series analysis of the short- to long-term effect.

3.3. Time series analysis: short- to long-term effect

When increasing the period around the threshold, the changes of the time-varying confounders could be so large that they have to be controlled for (Hausman and Rapson, 2018). In addition to the transmission capacity allocation methodology (FBMC versus ATC), the main variables affecting day-ahead cross-border exchanges and prices are day-ahead load, day-ahead wind and solar generation, commodity prices, generation unavailabilities, day-ahead generation by non-intermittent technologies, temperature per country, and commercial exchange volumes with non-CWE countries. For example, higher day-ahead total load in a specific CWE country, ceteris paribus, increases that country's day-ahead price and decreases its net exchange position. Lower solar and wind generation or more unavailable generation capacity has a similar effect. Changing commodity prices also affect prices and exchanges. For example, increasing gas and coal prices generally increases the electricity price in countries that have gas and coal power plants as the marginal generator (i.e. the price-setter) in their generation mix. As a result, those countries will see their net exchange position, ceteris paribus, decrease. We also explicitly include generation by non-intermittent technologies to control for changes in the generation mix driven by other factors, like resource availability, plant investments and closures, and changing bidding strategies of market players. Temperature is included to control for its effect on temperature-dependent dynamic line ratings. We further refer to these control variables as the market conditions as they reflect the composition of the supply and demand curves over time. We estimate the long-term effect of FBMC on cross-border exchanges X_t using the following empirical specification:

$$\begin{aligned}\overline{X}_t &= \beta_{FBMC}\, FBMC_t + \alpha_0 + \sum_c \alpha_{1,c}\, load_{t,c} \\ &+ \sum_c \alpha_{2,c}\, wind_{t,c} + \sum_c \alpha_{3,c}\, solar_{t,c} \\ &+ \sum_c \sum_g \alpha_{4,c,g}\, gen_{t,c,g} + \sum_c \sum_g \alpha_{5,c,g}\, unav_{t,c,g} \\ &+ \alpha_6\, p_{coal,t} + \alpha_7\, p_{gas,t} + \alpha_8\, p_{CO_2,t} \\ &+ \sum_c \alpha_{9,c} temperature_{t,c} + \sum_e \alpha_{10,e} nonCWE_e + \epsilon_t\end{aligned} \tag{3}$$

where index c indicates a CWE country (Belgium, France, Germany or the and e indicates a border between a CWE-country and a non-CWE-country in a specified direction. The long-term effect of the introduction of FBMC on X_t equals β_{FBMC}. $FBMC_t$ is a dummy variable equal to zero before the introduction of FBMC and one after. An identical approach applies to estimate the effect on Δp_t. As there are four countries, three conventional generation technologies, and fourteen commercial borders with non-CWE countries (each going in two directions) there are 68 hourly control variables (total load, solar, wind, temperature, and generation and unavailable capacity of coal, gas and nuclear) and three daily commodity price variables. In addition to these controls, the dependent variable has been controlled for time-fixed effects (hour-of-day, day-of-week and month-of-year) that are estimated using the full pre-FBMC sample to capture seasonality, like in the augmented local-linear and separate polynomials RDiT.

The identifying assumption of our long-term estimation is that we control for all variables that might influence cross-border exchanges or prices during our study period, like generation output and availability. Importantly, no important structural electricity market changes took place in CWE during our study period, as the Third Energy Package entered into force in 2009, while the Clean Energy Package was only adopted in 2019 (Meeus, 2020). In addition, no cross-border lines between CWE countries were built during our study period. Right after the end of our sample, a number of structural changes took place:

[9] This means that the impacts of seasonality on the dependent variable are first estimated on the full pre-FBMC sample and the residuals are saved. Then, a local linear specification is estimated using just the residuals for hours that are within the 60-days bandwidth.

completion of the 1500 MW Niederrhein–Doetinchem line between the Netherlands and Germany (2018), market splitting between Germany and Austria (2018), completion of the Allegro line between Belgium and Germany (2020), and the minimum 20% RAM requirement (2020). Some transmission lines between CWE and non-CWE countries were built during our sample, but this is controlled for by explicitly adding exchanges with all neighboring non-CWE countries to the time-series analysis.

4. Results: impact of flow-based market coupling

This section presents the impact of FBMC on cross-border exchanges X_t and price difference ΔP_t. We find that immediately after the introduction of FBMC, cross-border exchange increased with 1700 MWh/h on average, while the price difference among the countries decreased by 10.4 €/MWh on average. Two and a half years after the introduction of FBMC, observed cross-border exchange volumes were 440 MW lower than before the introduction of FBMC, while the price difference was still 3.5 €/MWh lower. However, when taking into account the changing market conditions, we find that the FBMC-methodology still led to a persistent increase of cross-border exchange with around 1150 MWh/h, while decreasing the price difference with around 2 €/MWh. After controlling for these exogenous market conditions, we estimate that FBMC increased surplus in the day-ahead markets of Central Western Europe by on average M€134 per year in the first 2.5 years following the introduction. Importantly, our analysis only focuses on the day-ahead market. Because of arbitrage between markets, FBMC might also have had an effect on intraday, real-time, and over-the-counter markets, as well as balancing, redispatch and congestion costs, but we leave this to further research.

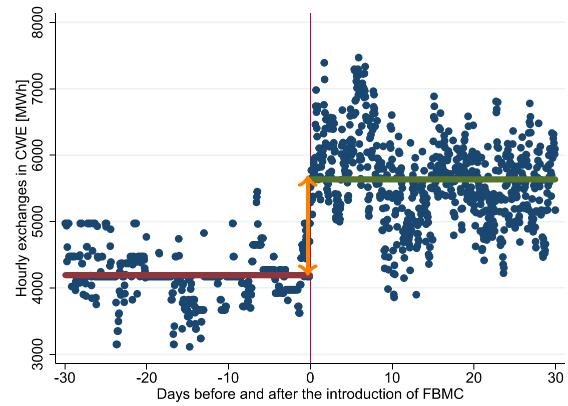
4.1. Short-term effect

4.1.1. Cross-border exchange volumes

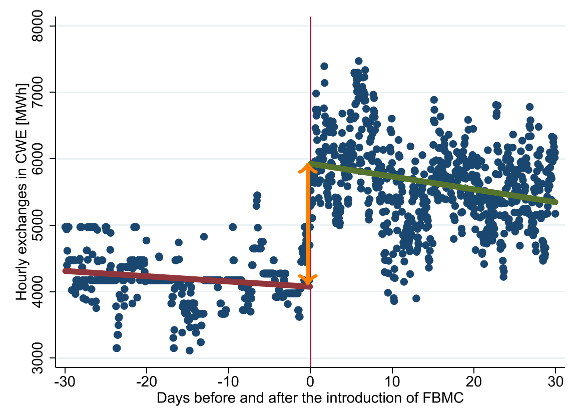
Fig. 3 shows RDiT plots for the three specifications introduced in Section 3. Panels (a) and (b) show X_t (as defined in Eq. (1)), and panel (c) shows residuals after controlling for time-fixed effects (seasonal effects have been filtered out). Panel (a) and (b) use a pre-post comparison of means (a) and a local linear approach (b), with 30 days of observations on either side of the threshold. Panel (c) uses a two-step augmented local linear approach, controlling for time-fixed effects (month, hour-of-day and day-of-week) estimated on the pre-FBMC sample, while the treatment effect is estimated with either just 30 days of observations on either side of the threshold (panel (c)).

The estimates of the policy effect vary slightly across specifications, but they are all positive and statistically different from zero. While the 'pre/post' specification (panel (a)) results in an estimated treatment effect of 1442 MWh/h, the 'local linear' specification (panel (b)) shows an effect of 1851 MWh/h. This is higher because the latter specification takes into account the decrease in X_t over time (see panel (b) and (c) in Fig. 3), which is stronger after the introduction of FBMC. Controlling for time-fixed effects, the 'augmented local linear' (panel (c)) estimates a treatment effect of 1917 MWh/h. Across these specifications, the average short-term treatment effect of the introduction of FBMC on cross-border exchange volumes amounts to 1737 MWh/h. This means that the hourly exchange of electricity between the CWE countries was on average 1737 MWh/h higher in the 30 days after the introduction of FBMC compared to the 30 days before. In relative terms, this is an increase of 44%.

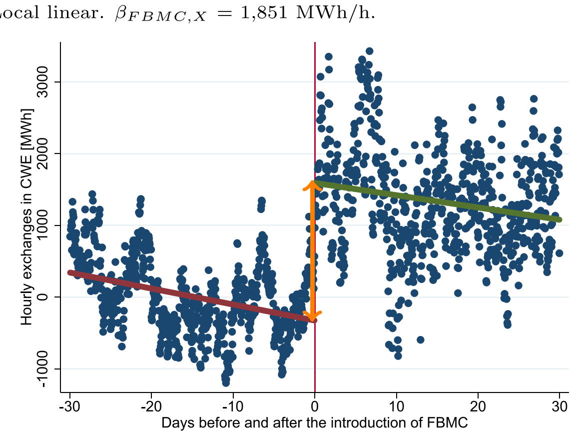
Looking at the average treatment effect of the individual countries over the three specifications, cross-border trade ($|NEP|$) increased significantly in the Netherlands (+2086 MWh/h on average), Germany (+1508 MWh/h on average) and France (+443 MWh/h on average), while there is a decrease in Belgium (−503 MWh/h on average). As Belgium and the Netherlands are generally importing and Germany is exporting, these results mean that imports in the Netherlands increased, imports in Belgium decreased, and exports from Germany increased in the 30 days after the introduction of FBMC.



(a) Pre/post. $\beta_{FBMC,X}$ = 1,442 MWh/h.



(b) Local linear. $\beta_{FBMC,X}$ = 1,851 MWh/h.

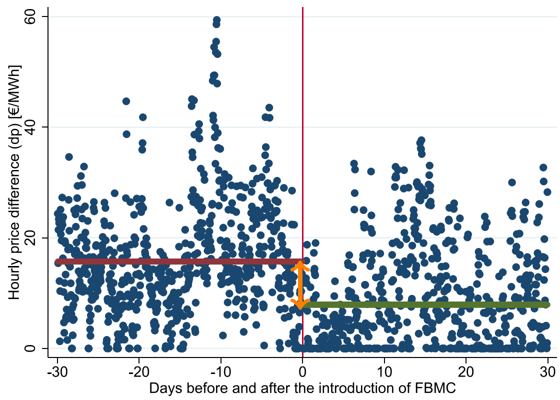


(c) Augmented local linear. $\beta_{FBMC,X}$ = 1,917 MWh/h.

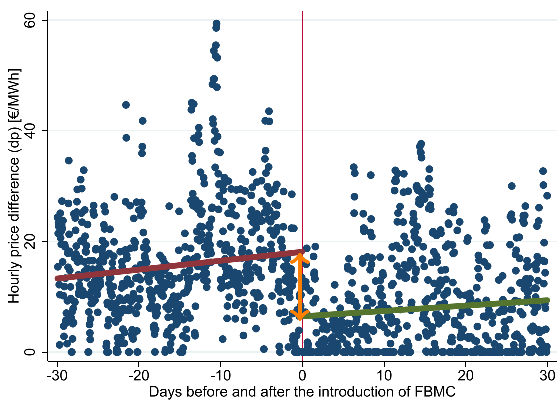
Fig. 3. Plot of three different regression discontinuity in time estimates of the effect of FBMC on the hourly cross-border exchange volume X_t as defined in Eq. (1). The treatment effect is indicated in orange. Note that the range on the y-axis varies. Across specifications, the short-term effect equals 1737 MWh/h.

4.1.2. Price differences

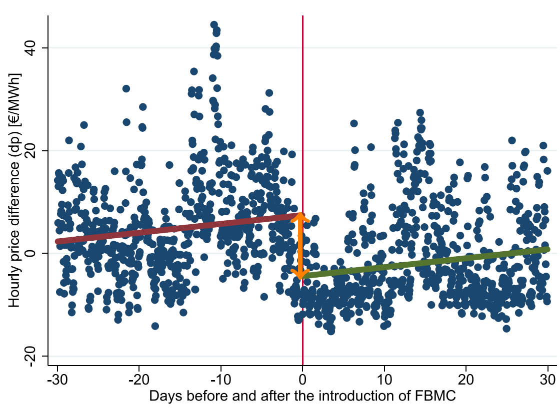
Fig. 4 shows the same three RDiT plots, but now for ΔP_t, the weighted price difference between market zones. The estimates of the policy effect vary slightly across specifications, but they are all negative and statistically different from zero, meaning that prices converge after the introduction of FBMC. The 'pre/post' specification (panel (a)) results in an estimated treatment effect of −7.8 €/MWh. On the other hand, the 'local linear' (panel (b)) and 'augmented local linear' (panel (c)) specifications show a larger effect of around −11.7 €/MWh, as there is an increasing trend in price differences ΔP_t right before and after the introduction of FBMC. Across these specifications, the



(a) Pre/post. $\beta_{FBMC,\Delta P}$ = -7.8 €/MWh.



(b) Local linear. $\beta_{FBMC,\Delta P}$ = -11.6 €/MWh.



(c) Augmented local linear. $\beta_{FBMC,\Delta P}$ = -11.8 €/MWh.

Fig. 4. Plot of three different regression discontinuity in time estimates of the effect of FBMC on the hourly weighted price difference ΔP_t. Note that the range on the y-axis varies. Across specifications, the short-term effect equals −10.4 €/MWh.

average short-term treatment effect of the introduction of FBMC on price differences ΔP_t among CWE countries equals −10.4 €/MWh, meaning that the introduction of FBMC had a clear positive effect on price convergence in the CWE region.

Looking at the individual CWE countries, we observe that the average price decreased by 10.5 €/MWh and 6.6 €/MWh in, respectively, Belgium and the Netherlands, and increased by 1.5 €/MWh and 4.4 €/MWh in, respectively, Germany and France. This is in line with the short-term effect on cross-border exchange volumes X_t. Specifically, Belgium and The Netherlands are importing countries (see Table 1), while Germany structurally exports and France exports around half of the time.

4.2. Short- to long-term effect

We have shown that right after the introduction of FBMC exchange volumes increased on average by 1737 MWh/h in CWE and prices converged by 10.4 €/MWh. In this section, we discuss the long-term evolution of cross-border exchange volumes and price differences among the CWE countries. Importantly, we make a distinction between the evolution of the *observed* cross-border exchange volumes and prices, and their *estimated* evolution after controlling for changing market conditions throughout our sample.

Fig. 5 shows the 95% confidence interval of the evolution of the average cross-border exchange volume X and weighted price difference ΔP over time. We compare the average X and ΔP in the sample up to t days after the introduction of FBMC with the average X and ΔP before (1 January 2015–20 May 2015) the introduction, with and without controlling for market conditions and time-fixed effects. This means that the post-FBMC sample is gradually increasing in size as we consider more days after the introduction. For example, the value at 200 days indicates the average increase of X and ΔP over the 200 days post-FBMC sample, compared to the pre-FBMC sample (140 days). The blue line presents the change in observed cross-border exchange volumes after the introduction of FBMC, while the red line controls for market conditions, using Eq. (3).

4.2.1. Cross-border exchange volumes

Fig. 5(a) presents the long-term effect on cross-border exchange volumes X. It shows that the observed cross-border exchange X in CWE (blue) immediately jumped up with around 1318 MWh/h right after the introduction of FBMC[10], but then steadily decreased. By the end of 2017, the observed cross-border exchange X decreased to 440 MWh/h less than the average value between 1 January 2015–20 May 2015.

If we control for changing market conditions (e.g., changing renewable generation, commodity prices, generation asset outages) the picture is different. After an initial decrease of around 700 MWh/h, largely following observed exchange volumes, additional exchange volumes stabilize at around 1150 MWh/h when changing market conditions are taken into account. This means that, if market conditions would have stayed the same, the introduction of FBMC would have increased cross-border exchange volumes by around 1150 MWh/h on average over our post-FBMC sample. But because of changing market conditions, that are independent of the introduction of FBMC, the observed exchange volumes have decreased by around 1440 MWh/h between 21 May 2015 and 31 December 2017. This means that the observed decrease of cross-border exchange after the introduction of FBMC is not due to the FBMC-methodology, but to changes in other external market conditions, like changes in the distribution of the generation dispatch.

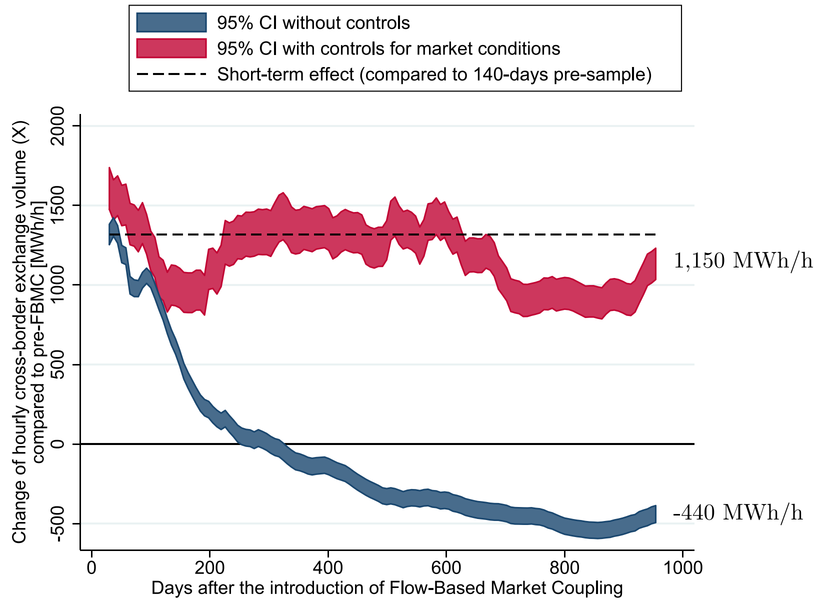
4.2.2. Price differences

Fig. 5(b) shows the long-term effect on the average price difference ΔP. It shows that the observed demand-weighted price difference ΔP immediately jumped down with around 6 €/MWh on average right after the introduction of FBMC.[11] By the end of 2017, the observed price difference ΔP slightly increased to around 3.5 €/MWh less than the average value between 1 January 2015–20 May 2015, as already presented in Table 1.

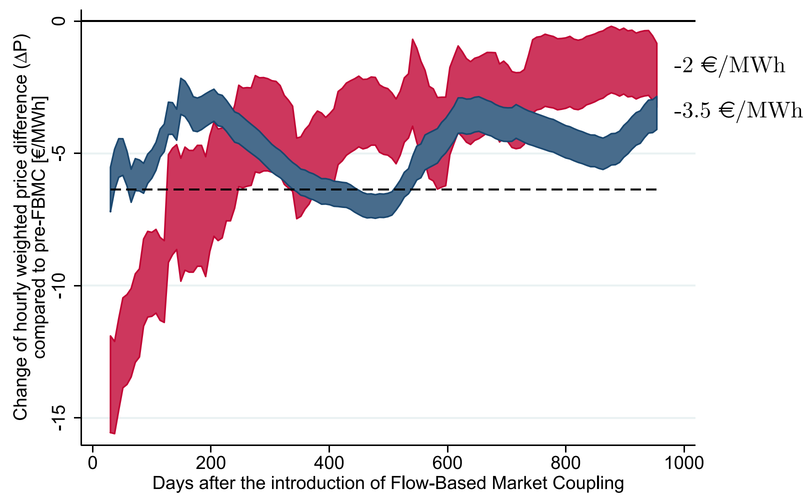
Controlling for changing market conditions, the introduction of FBMC still increases price convergence. Initially, estimated prices

[10] Note that this value is slightly lower than the one estimated in Section 4.1. This is because it was estimated on a 30-day pre-FBMC sample, following the guidelines on RDit (Hausman and Rapson, 2018), while here we consider 140 days, to maximize the number of pre-FBMC data points.

[11] Note that this value is considerably lower than the one estimated in Section 4.1. This is because it was estimated on a 30-day pre-FBMC sample, following the guidelines on RDit (Hausman and Rapson, 2018), while here we consider 140 days, to maximize the number of pre-FBMC data points.



(a) Cross-border exchange volume X. After an immediate increase of around 1,318 MWh/h in cross-border exchange volumes after the introduction of FBMC, observed exchange volumes (blue) gradually decrease by 2,000 MWh/h, fully offsetting the initial benefits of FBMC. However, taking into account market developments (red), additional exchange volumes stabilize at around 1,150 MWh/h, after a first drop.



(b) Average of weighted price difference ΔP. After an immediate decrease of around 6 €/MWh in price differences after the introduction of FBMC, a slight increase to 3.5 €/MWh less than the weighted price difference in the period prior to FBMC followed. Controlling for market conditions, the effect of FBMC still decreases price differences.

Fig. 5. Evolution of the average cross-border exchange volume X_t and weighted price difference ΔP_t over time. We compare the average X_t and ΔP_t in the sample up to t days after the introduction of FBMC with the average X_t and ΔP_t before (1 January 2015–20 May 2015) the introduction, with and without controlling for market conditions.

converge more than observed prices,[12] but over the full 2015–2017 sample, the estimated price convergence is slightly lower than the observed one. This means that when market conditions would have remained constant and equal to the period prior to the introduction of FBMC, the introduction of FBMC would still have decreased the price difference.[13]

Note that the blue and red lines differ significantly right after the introduction of FBMC, especially for ΔP_t. This is because of changes in confounding variables during the first 30 days after the introduction of FBMC. Specifically, we find that the difference is almost completely driven by changes in two variables: the lower unavailability of nuclear capacity in Germany and the higher unavailability of gas capacity in France. Because the electricity price is generally lower in Germany than in France, these outages increase the observed price difference and hence the observed price convergence is less than if market conditions would have stayed the same. This highlights the importance of controlling for changing market conditions.

[12] This is because market conditions do not change perfectly smoothly in the first month after the introduction of FBMC, as was discussed in Section 3.2. For example, total generation in Germany is 1200 MWh/h lower in the month after the introduction of FBMC, as can be seen in Table A1. Because Germany is structurally exporting, decreased generation increases observed price differences, hence lowering the observed benefits of FBMC. The main drivers of the difference between observed and estimated price convergence are a 600 MWh/h increased generation in Belgium (−1.7 €/MWh), a 1205 MWh/h decreased generation in Germany (+3.9 €/MWh), a 971 MWh/h increased generation in France (+1.9 €/MWh), a 591 MWh/h decreased generation in the Netherlands (+1.6 €/MWh), and a 345 MWh/h increased export from Germany to Italy (+1.1 €/MWh).

[13] In B we provide the intuition of how the estimated price convergence can be less than the observed convergence, even when the estimated exchange volumes are higher.

4.3. The effect on day-ahead market surplus

A change in traded volumes and prices impacts day-ahead market surplus. The benefits of the introduction of FBMC consist of three components: the change in producers' surplus PS, consumers' surplus CS and congestion rent CR. The congestion rent is non-zero in case of a remaining price difference between countries. See C for more information on the calculation of the benefits.

We do the calculation using both the short-term and long-term effect of FBMC and control for the changing market conditions. Focusing on the long term, the introduction of FBMC increased the market surplus by M€134 per year or €15,295 per hour when controlling for changing market conditions. This is more than the increase in economic surplus of M€95 per year that was estimated by the TSOs during the parallel runs before the go-live of FBMC (Amprion et al., 2015). However, the study of the TSOs does not include congestion rent and focuses on producers' and consumers' surplus which does not capture the entire market surplus. In contrast, the observed long-term benefits are negative, as the observed cross-border exchanges decrease after the start of FBMC. In the short term, on the other hand, we estimate that the introduction of FBMC increased market benefits by M€158 per year or €18,113 per hour while controlling for the changing market conditions. Hence, the long-term day-ahead market surplus is only 84% of the short-term surplus. The difference is driven by the decreased effect of FBMC on cross-border exchange volumes over time.

5. Discussion

Despite decreased observed cross-border exchange volumes in CWE, the FBMC-methodology has a clear positive impact on both cross-border exchange volumes and price convergence, as Section 4 shows. While this paper is the first empirical analysis on the performance of FBMC, our results are in line with theory on cross-border trade of electricity. Specifically, the FBMC-methodology allows for more commercial transmission capacity that is available for trade in the day-ahead market, because it comes with a better grid representation as Section 2 outlines. However, we observe that the benefits of the FBMC-methodology are smaller in the longer term than in the short term. Specifically for the cross-border exchange volumes, we find that by the end of 2017, around 70% of the initial gains from FBMC still remain. The other 30% dissipated. In this section, we discuss the lost benefits of FBMC in the longer term.

Fig. 6 presents the average commercial transmission capacity, the so-called Remaining Available Margin (RAM), on the critical transmission lines after the introduction of FBMC.[14] We observe that within the first five months after the introduction of FBMC, the average RAM decreases from around 1550 MW to 1250 MW. A lower average RAM implies a smaller feasible space for cross-border exchange volumes under FBMC. As the RAM parameter is only available after the introduction of FBMC, we cannot explicitly control for this in our long-term estimation using Eq. (3). However, there is a strong positive correlation (0.49) between exchange volumes after controlling for market conditions (the red line in Fig. 5(a)) and the average RAM. Specifically, both the red line in Fig. 5(a) and the RAM in Fig. 6 first decrease in the four months after the introduction of FBMC and then stay approximately constant. This is in line with reports from regulators (CREG, 2017). Obviously, the same conclusion can be drawn for the price difference. There exists a strongly negative correlation (−0.89) between the average RAM and the effect of FBMC on price differences after controlling for market conditions (red line in Fig. 5(b)).

[14] We define the average RAM per hour as the sum of RAMs over all reported critical branches divided by the number of critical branches in that hour. Specifically, we use data from the utility tool from the TSO platform ().

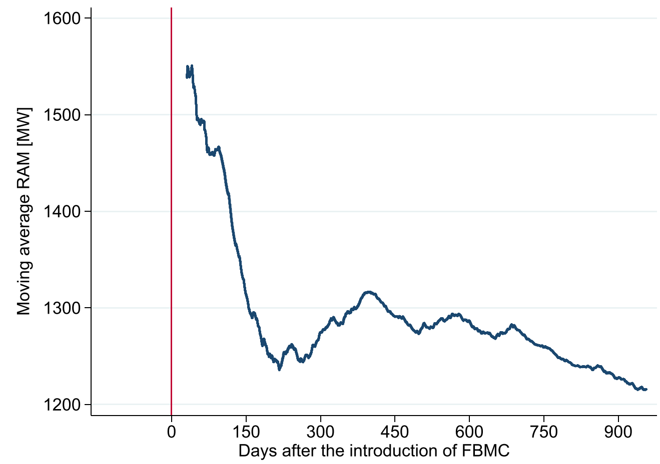


Fig. 6. The average remaining available margin (RAM) in CWE, defined as the sum of RAMs over all reported critical branches divided by the amount of critical branches in that hour, for gradually increasing sample periods after the introduction of FBMC. The moving average first steeply decreases in the four months after the introduction of FBMC and then stay approximately constant.

The RAMs on critical lines are set by the TSOs, based on their assessment of loop flows and safety margins (see Section 2). As said before, TSOs make a trade-off between real-time reliability of the system (which typically calls for less commercial exchanges) and economic efficiency (which requires more commercial exchanges) (Ovaere and Proost, 2018). The decreased RAMs in the months after the introduction of FBMC indicate that TSOs gradually adjusted their trade-off between efficiency and reliability. To manage this trade-off and guarantee that sufficient transmission capacity is made available for trade (Marien et al., 2013), different forms of regulation exist. First, since 2018 there is a European MinRAM criterion that requires that RAM on each critical branch is at least 20% of its physical transmission capacity. By 2025, this will be expanded toward 70% (Council of the European Union and European Parliament, 2019). MinRAM criteria could be an effective measure, but different studies have argued that they might not always lead to the welfare-optimal determination of the TSO parameters, as they are static over time (Henneaux et al., 2021; Matthes et al., 2019; Schönheit et al., 2020a). MinRAM criteria should be based on a careful techno-economical analysis, which is currently not the case in Europe. Moreover, a lot of derogations exist in practice which strongly lowers the effectiveness of the measure (e.g., in case of loop flows, the Belgian TSO can deviate from the MinRAM criterion (CREG, 2020)). Second, there exist direct monetary incentives for different aspects of TSO behavior, like reliability, redispatch costs, available cross-border transmission capacity, and commercial cross-border exchanges (Kenis et al., 2021; Ovaere, 2017).

In addition to TSOs decreasing RAMs over time, other market participants might also have changed their behavior over time, like adjusting their bidding strategies and learning about arbitraging price differences between the day-ahead, intraday, real-time, and over-the-counter markets. This goes beyond the scope of the paper.

6. Conclusion

Using regression discontinuity in time and a time-series approach, we empirically estimate the short- and long-term effect of FBMC on electricity cross-border exchange and price convergence in the Central Western European electricity markets. We find that immediately after the introduction of FBMC, cross-border exchange increased with 1700 MWh/h on average, while the price difference among the countries decreased with −10.4 €/MWh on average. As expected, the price in the

Table A1
Mean and standard deviation of the control variables 30 days before and 30 days after the introduction of FBMC, as well as the difference between the means before and after the introduction of FBMC. Not in the table: load in each country (difference less than 4%), coal price (difference is 3.7%), gas and carbon price (no difference), temperatures (small difference) as well as exchanges with non-CWE countries (small differences).

Variable	Pre-FBMC		Post-FBMC		Difference	
	Mean	Std. dev.	Mean	Std. dev.	Absolute	Relative
Renewable generation [MWh/h]:						
$wind_{t,BE}$	487	(375)	469	(371)	−18	−3.6%
$wind_{t,DE}$	6736	(4466)	5674	(4087)	−1062	−15.7%
$wind_{t,FR}$	1954	(1147)	1797	(993)	−157	−8.0%
$wind_{t,NL}$	720	(538)	741	(587)	21	2.9%
$solar_{t,BE}$	510	(622)	622	(704)	112	21.9%
$solar_{t,DE}$	6151	(7376)	6574	(7239)	423	6.9%
$solar_{t,FR}$	1059	(1230)	1192	(1301)	133	12.6%
$solar_{t,NL}$	172	(212)	204	(230)	32	18.6%
Conventional generation [MWh/h]:						
$gas_{t,BE}$	2048	(401)	1799	(309)	−249	−12.2%
$gas_{t,DE}$	587	(260)	680	(249)	93	15.8%
$gas_{t,FR}$	904	(176)	768	(127)	−136	−15.0%
$gas_{t,NL}$	1063	(694)	686	(515)	−377	−35.5%
$coal_{t,BE}$	179	(127)	0	(0)	−179	−100.0%
$coal_{t,DE}$	12842	(1582)	12703	(1477)	−139	−1%
$coal_{t,FR}$	357	(474)	55	(137)	−302	−84.6%
$coal_{t,NL}$	308	(176)	258	(168)	−50	−16.2%
$nuclear_{t,BE}$	2499	(439)	3438	(28)	939	37.6%
$nuclear_{t,DE}$	9508	(420)	8986	(424)	−522	−5.5%
$nuclear_{t,FR}$	40805	(3086)	42237	(3143)	1432	3.5%
$nuclear_{t,NL}$	374	(238)	160	(244)	−214	−57.4%
Unavailable generation capacity [MW]:						
$unavnuclear_{t,BE}$	2950	(475)	2014	(6)	−936	−31.7%
$unavnuclear_{t,DE}$	1503	(428)	489	(670)	−1014	−67.5%
$unavnuclear_{t,FR}$	18083	(1698)	16729	(1483)	−1354	−7.5%
$unavnuclear_{t,NL}$	0	(0)	0	(0)	0	0%
$unavgas_{t,BE}$	650	(203)	785	(451)	135	20.8%
$unavgas_{t,DE}$	4141	(239)	2709	(707)	−1432	−34.6%
$unavgas_{t,FR}$	3217	(512)	3529	(163)	312	9.7%
$unavgas_{t,NL}$	2545	(309)	2703	(177)	158	6.2%
$unavcoal_{t,BE}$	190	(133)	370	(0)	180	94.7%
$unavcoal_{t,DE}$	8301	(1604)	6646	(1112)	−1655	−19.9%
$unavcoal_{t,FR}$	3441	(336)	3673	(167)	232	6.7%
$unavcoal_{t,NL}$	1047	(434)	1157	(510)	110	10.5%
Observations	720		720		1440	

exporting countries (Germany and France) increases, while it decreases in the importing countries (Belgium and The Netherlands).

Two and a half years after the introduction of FBMC, observed cross-border exchange volumes were 440 MW lower than before the introduction of FBMC, while the price difference was still 3.5 €/MWh lower. However, when taking into account the changing market conditions, we find that the FBMC-methodology still led to a persistent increase of cross-border exchange with around 1150 MWh/h, while decreasing the price difference with around 2 €/MWh. The exogenous drivers of the changing market conditions include load, wind and solar generation, generation of nuclear, gas and coal power plants, unavailability of nuclear, gas and coal power capacity, coal, gas and carbon prices, temperatures, as well as exchanges with non-CWE countries. After controlling for these exogenous market conditions, we estimate that FBMC increased surplus in the day-ahead markets of Central Western Europe by on average M€134 per year in the first 2.5 years following the introduction.

There exists a large difference between the long-term (M€134 per year) and short-term (M€158 per year) increase of day-ahead market benefits of the introduction of FBMC. We provide subjective evidence that decreased commercial transmission capacity (RAM) on critical lines, set by TSOs, might have contributed to the decline of the benefits over time. Therefore, regulatory intervention (e.g., MinRAM criteria or incentive regulation) might be beneficial to tap the full potential of cross-border trade. These insights are useful for policy makers, regulators, TSOs, market participants and other stakeholders, especially in light of the extension of FBMC to other regions as it is the target methodology toward a European single electricity market.

The methodology in this paper can be applied to empirically evaluate the realized short- and long-term benefits of any treatment. This can include, but is not limited to, policy changes (e.g., the inclusion of minimal trading capacities) or the introduction of new interconnections (e.g., NEMO-project between the UK and Belgium (Nemolink, 2021)).

CRediT authorship contribution statement

Marten Ovaere: Conceptualization, Methodology, Data curation, Software, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Michiel Kenis:** Methodology, Data curation, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Kenneth Van den Bergh:** Conceptualization, Methodology, Writing – original draft. **Kenneth Bruninx:** Writing – review & editing. **Erik Delarue:** Funding acquisition.

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Appendix A. Control variables in the short term

Table A1 shows the mean and standard deviation of the control variables 30 days before and 30 days after the introduction of FBMC,

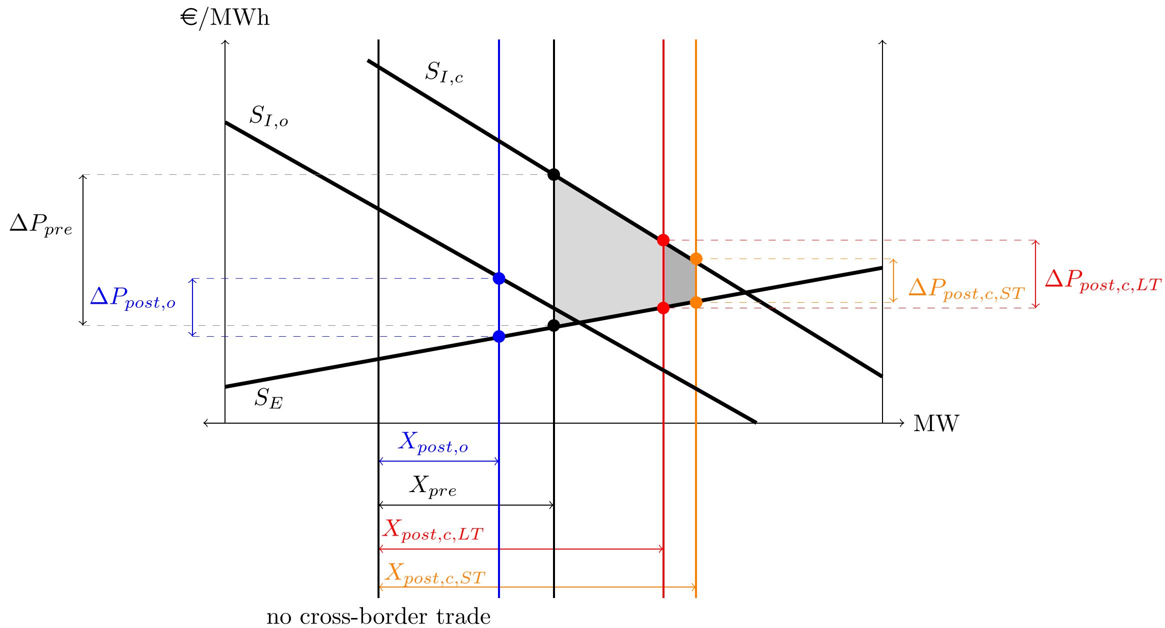

Fig. B.1. Economic interpretation of cross-border trade before and after FBMC, with and without controlling for market conditions for two interconnected countries. Before the introduction of FBMC, there is cross-border exchange X_{pre} and price difference ΔP_{pre}. After the introduction of FBMC, in the long term, we observe a decreased cross-border exchange $X_{post,o}$. Depending on the changing market conditions, represented by a downward shift of the importing country's supply curve from $S_{I,c}$ to $S_{I,o}$, the observed price difference $\Delta P_{post,o}$ might be lower or higher than the short-term and long-term price differences $\Delta P_{post,c,ST}$ and $\Delta P_{post,c,LT}$ when controlling for changing market conditions. In addition, the price difference $\Delta P_{post,o}$ might actually decrease, despite the decreased cross-border exchange.

as well as the difference between the means before and after the introduction of FBMC. The lower unavailability of nuclear capacity in Germany, among others, varies significantly (decrease of 67.5%). Because the electricity price is generally relatively lower in Germany, these outages increase the observed price difference.

Appendix B. Relationship between cross-border exchanges and price differences

Section 4.2 presents that, on average since the introduction of FBMC until the end of 2017, both the observed cross-border exchange X and price difference ΔP fell to levels below the period prior to FBMC, while one intuitively expects an inverse relation between X and ΔP. Using Fig. B.1 we will explain this non-obvious relationship between observed cross-border exchanges and prices, when market conditions change over time. Fig. B.1 presents the illustrative electricity supply curve of an exporting country E (S_E, from left-to-right) and of an importing country I (S_I, right-to-left). For the sake of simplicity, we assume a two-country system in which the zonal (national) markets of country E and country I are coupled. This means that the x-axis represents the demand in each country and how much is being exchanged between them. The y-axis represents the price of electricity in country E (left axis) and country I (right axis).

First, suppose that before the introduction of FBMC, there is cross-border exchange X_{pre} and a price difference ΔP_{pre} between both countries. If after the introduction of FBMC we observe a decreased cross-border exchange $X_{post,o}$ and market conditions shift the supply curve of the importing country downward from $S_{I,c}$ to $S_{I,o}$, without affecting S_E, the price difference $\Delta P_{post,o}$ might actually decrease, despite the decreased cross-border exchange. On the other hand, suppose that, when controlling for the changing market conditions (i.e. taking the same market conditions as prior to the introduction of FBMC), cross-border exchange $X_{post,c,ST}$ (for short-term) and $X_{post,c,LT}$ (for long-term) would have been higher than before FBMC, just like we found in Section 4.2.1. In this case, controlling for market conditions implies that the original supply curve $S_{I,c}$ is still applicable, which means that depending on the changing market conditions, the counterfactual $\Delta P_{post,c,ST}$ and $\Delta P_{post,c,LT}$ might be lower or higher than the observed price difference $\Delta P_{post,o}$.

Appendix C. Calculation of the effect on day-ahead market surplus

The long-term and short-term benefits of cross-border trade under the FBMC-methodology compared to the ATC methodology, while controlling for changing market conditions, are equal to the colored areas in Fig. B.1, and the mathematical equations read as follows:

$$\begin{aligned}\Delta B_{LT} = {} & \Delta P_{post,c,LT} \times \left[X_{post,c,LT} - X_{pre}\right] \\ & + \frac{1}{2}\left[\Delta P_{pre} - \Delta P_{post,c,LT}\right] \times \left[X_{post,c,LT} - X_{pre}\right] \\ \Delta B_{ST} = {} & \Delta B_{LT} + \Delta P_{post,c,ST} \times \left[X_{post,c,ST} - X_{post,c,LT}\right] \\ & + \frac{1}{2}\left[\Delta P_{post,c,LT} - \Delta P_{post,c,ST}\right] \times \left[X_{post,c,ST} - X_{post,c,LT}\right]\end{aligned}$$

with X_{pre} the average cross-border exchange volumes before the introduction of FBMC and $X_{post,c,ST}$ and $X_{post,c,LT}$ the average cross-border exchange volumes respectively 30 days and around 2.5 years after the introduction of FBMC while controlling for the changed market conditions. Similarly, ΔP_{pre}, $\Delta P_{post,c,LT}$ and $\Delta P_{post,c,ST}$, represents the average price differences before, after 30 days, and after around 2.5 years.

The light gray area in Fig. B.1 represents the long-term increase of day-ahead market benefits, while the light and dark gray areas together represent the short-term increase of day-ahead market benefits. In our calculation of the increased market benefits, we take a first-order linear approximation of the supply curve.

Focusing on the long term, the introduction of FBMC increased the market surplus by M€134 per year or €15,295[15] per hour when

[15] Section 4.2.1 shows that $X_{post,c,LT} - X_{pre}$ equals 1150 MWh/h, Section 4.2.2 shows that $\Delta P_{pre} - \Delta P_{post,c,LT}$ amounts to 2 €/MWh, and together with Table 1, it reports that $\Delta P_{post,c}$ is 12.3 €/MWh (14.3 €/MWh minus 2 €/MWh).

controlling for changing market conditions. In the short term, on the other hand, we estimate that the introduction of FBMC increased market benefits by M€158 per year or €18,113 per hour.[16]

Appendix D. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106519.

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[16] Fig. 5 shows that $X_{post,c,ST}$ amounts to 5923 MWh/h and $\Delta P_{post,c,ST}$ amounts to 0.6 €/MWh per hour. Note that the increased short-term benefits, calculated from observed changes in exchanges and price convergence is somewhat lower than when controlling for market conditions (€16,934 per hour versus €18,113 per hour), because the observed price convergence in the short term is less than the estimated price convergence, as shown in Fig. 5.