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The flow based market coupling arrangement in Europe: Implications for traders☆

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ABSTRACT

A new method for congestion management, flow based market coupling (FBMC), launched on May 21, 2015 in the Central Western European (CWE) region. Prior to this, no similar congestion method has been implemented elsewhere. FBMC models the electrical network, considering cross-border exchanges including security constraints. The flows span all available parallel paths as governed by the laws of physics. The objective is to optimize market flows and social welfare. FBMC allocates cross-border flows considering power transfer distribution factors (PTDFs) which describe the sensitivity of a change in import/export at a particular country. The PTDF matrix and the remaining available margin (RAM) determine the feasible transmission region at any given point in time. On a daily basis, the Capacity Auctioning Service Company (CASC) gives information about maximum bilateral exchanges, minimum and maximum net positions and PTDFs for the day-ahead market. This daily tool serves as a framework for analyzing potential congestion in the CWE region and price coupling of markets in individual hours. We explain how traders can apply the CASC tool to analyze potential congestion and identify trade opportunities. We discuss some approaches to analyze the FBMC beyond the day-ahead market.

1. Introduction

This paper gives an overview and analysis of flow based market coupling (FBMC), a new method for managing congestion in the Central Western European (CWE) region We analyze the results of the parallel runs from 2013 to 2015 including the operational runs from its inception on May 21, 2015 to March 31, 2016. During the parallel runs, flow based parameters were computed in parallel with available transmission capacities (ATCs) and used to run market coupling simulations, based on the same order books of the power exchanges. On a daily basis, the Capacity Auctioning Service Company (CASC) gives information about maximum bilateral exchanges, minimum and maximum net positions and PTDFs for the day-ahead market. This online tool serves as a framework for analyzing potential congestion in the CWE region and price coupling of markets in individual hours. Although FBMC has added more complexity to electricity market analyses and trading, it provides previously unavailable data to analyze transmission congestion and price differentials. Beyond the day-ahead market, FBMC implies highly inter-related flows and integration of the entire CWE region.

The structure of the paper is as follows. Section 2 describes the history of market coupling in Europe. Section 3 briefly reviews the literature on FBMC. Section 4 provides a mathematical overview of FBMC. Section 5 analyzes the results of the FBMC parallel runs from 2013 to 2015 and compares the prices to the ATC method. Section 6 outlines some analytical frameworks for FBMC. Section 7 analyzes the results from the operational FBMC from May 21, 2015 to March 31, 2016. Section 8 discusses the implications and explains how traders can apply the CASC to analyze potential congestion and identify trade opportunities. Section 9 concludes.

2. History of market coupling

Initially, cross-border trading among the Central Western European (Germany, France, the Netherlands and Belgium, or CWE) electricity markets involved auctioning cross-border capacity to the market separately and independently from the electricity trading market place [1]. Thus, it occurred that flows could go from high to low price areas if the market participants' price expectation was incorrect. After November 22, 2006, when the tri-lateral market coupling (TLC) among France, Belgium and the Netherlands was implemented [1,2], implicit capacity auctioning was undertaken by only trading energy for the day-ahead market. The arrangement can best be described as a single centralized

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price coupling system that calculated market prices and trading volumes, based on available cross-border capacity and the order books of the power exchanges. The objective was to maximize social welfare subject to ATC. The ATC, which indicated the maximum capacity that could be exchanged commercially across a border in a given direction, only considered bilateral transactions and above already committed utilization. Mathematically, ATC equals the total transfer capability (TTC) less the transmission reliability margin (TRM) and less the sum of existing long-term nominations. Thus, TSOs had to choose how to split the capacity among the borders of France, Belgium and the Netherlands, and eventually the minimum ATC value was selected. However, the feasible region was generally more restrictive than under FBMC because the simplified modelling neglected many electrical characteristics.

On November 9, 2010 the day-ahead ATC market coupling for the CWE region (Germany, France, the Netherlands and Belgium) was implemented [1,3]. Basically, an extension of TLC, it included Germany with similar price and flow calculations. Finally, on May 21, 2015, the flow based market coupling (FBMC) was implemented for the CWE region. FBMC models the electrical network, considering cross-border exchanges including security constraints [2]. The flows span all available parallel paths as governed by the laws of physics. The objective is to optimize market flows and social welfare.

3. Literature review

Bergh et al. [4], who describe the concepts and definitions utilized in FBMC, observe that the methodology is complex and poorly understood. Market participants rate their own understanding at an intermediate level [5]. Aguado et al. [6] use FBMC to evaluate historical order books and conclude that the transmission capacity made available is larger under FBMC than ATC. Waniek et al. [7] reach similar conclusions. Marien et al. [8] demonstrate that FBMC's parameters have substantial impacts on market outcomes. Thus, they argue for transparency and monitoring of the FBMC calculation process. SINTEF Energy [9] perform simulations using a flow-based model called Samnett to investigate the possible advantages of FBMC compared to ATC; the results show that Samnett has more efficient use of the grid and lower price differences and provides a higher socio-economic surplus than the Samlast (ATC) model.

4. Mathematical formulation of flow based market coupling

FBMC uses the physical transmission constraints of the electrical network and allocates cross-border flows, considering the power transfer distribution factors (PTDFs) which provides sensitivity information about a change in import/export at a particular hub or country [10]. The PTDF matrix and remaining available margin (RAM) determine the feasibility region (or security domain) at any given point in time. The maximum exchange values are generally greater than the ATC values but cannot be allocated simultaneously.

With FBMC it is theoretically possible that power flows from a high price area to a low price area if this increases social welfare, and the flows obey the laws of physics. However, this is not possible because FBMC's current implementation (intuitive) enforces exporting from the most inexpensive markets, albeit at the cost of lower social welfare.

FBMC's important concepts are as follows [10]:

Generation shift key (GSK): Best estimate of how a country's total generation is distributed among the generators within the country or area.

Power transfer distribution factor (PTDF): Specifies the incremental flow of a 1 MW transaction between two hubs (for example A and B) on a given critical branch (CB).

Critical branch (CB): A transmission network element (line, transformer, or a normal or contingency operational situation) by cross-border trade and monitored under operation; determination of each CB's available physical capacity is based on the physical limit of the line and considering necessary security margins.

Critical branches/critical outages (CBCOs): Tripping of a line, cable, transformer, busbar, generating unit, significant load, or k elements; also contingency cases (N-1, N-2) representing outages.

Remaining available margin (RAM): Maximum flow minus the flow in the base case including long term capacities and minus the flow reliability margin; RAM specifies the free margin for every cross-border.

Modelling the entire grid, including contingency scenarios, would amount to a large number of constraints and be computationally burdensome. Thus, modelling limits the number of constraints to the critical branches that are significantly affected by cross-border trade and that potentially could become congested due to grid security reasons. Congestion in FBMC is not only monitored on borders, but also on critical branches that are internal to countries.

4.1. Definitions

$cb \in CB$: one critical branch cb as a subset of all critical branches CB
$z \in CWE$: zone z as a subset of all CWE zones
$b \in B$: bidder b as a subset of all bidders B
$PTDF^z_{cb}$: the PTDF of zone z on a critical branch cb
nex_z: the net import/export position of zone z
RAM_{cb}: the allocated margin on critical branch cb
(Q^z_b, P^z_b) : the bid of bidder b in area z. The quantity Q^z_b in MW is negative if it is a supply bid and positive if it is a demand bid. The price P^z_b is in €/MW
x^z_b: the accepted part of the bid b, between 0 and 1

4.2. Objective function

Mathematically the objective function equals three components: seller surplus, buyer surplus and congestion revenue defined as [10]:

$$max \sum_{x \in CWE} \sum_{b \in B} Q^z_b P^z_b x^z_b \tag{1}$$

Power exchanges provide order books. The decision variables are the net positions in the CWE region (Germany, France, the Netherlands and Belgium) and the accepted part of the bids.

4.3. Constraints

The sum of the net positions must equal zero. A positive net position indicates exports and a negative indicates imports.

Mathematically, the balancing constraint ensuring that supply equals demand bids is:

$$\sum_{z \in CWE} nex_z = 0, \tag{2}$$

where

$$nex_z = -\sum_{b \in B} Q^z_b x^z_b \tag{3}$$

The flow based constraints limit the CBCO's flow [10].

$$\sum_{z \in CWE} PTDF^z_{cb} \cdot nex_z \leq RAM_{cb} \qquad \forall cb \in CB. \tag{4}$$

If the social welfare is maximized without any binding constraints, the RAMs of the critical branches can support all market transactions. In this case the prices are equal in all four zones.

Conversely, if a constraint is active (RAM is fully allocated), transmission congestion occurs, and the price in each zone is related to the magnitude of the PTDFs of the critical branch. The binding constraint has a shadow price which represents the increase in social welfare caused by making 1 MW more capacity available to the market. The country price differentials are proportionate to the sensitivity (i.e. shadow price) it has on the constraint as well as the relative difference in PTDFs [10]:

$$\frac{P_z - P_y}{PTDF_y - PTDF_z} = shadow\ price \geq 0, \tag{5}$$

where zones z and y are a subset of all *CWE* zones. A single active constraint is therefore sufficient to create four different prices since dispatch has to be adjusted to avoid overloading transmission lines. The zonal prices will then be calculated on that adjusted dispatch. For a given constraint, the smaller the *PTDF*, the higher the price will be in that zone [10]:

$$PTDF_z > PTDF_y \rightarrow P_y > P_z. \tag{6}$$

The equations reflect the physics of the electrical network and prioritize the exchanges using the least transmission capacity. Exchange bids related to a hub with a smaller PTDF over a critical branch will have priority even if their price is higher than a similar exchange bid related to a hub with a higher PTDF over the same critical branch [10].

The price properties of FBMC are generalized as:

$$P_z - P_y = \sum_{cb \in CWE} (PTDF_y - PTDF_z)\mu_{cb}, \tag{7}$$

where μ_{cb} is the shadow price of the critical branch. Eq. (7) states that the price difference between two locations y and z is equal to the sum over all congested branches of the PTDF difference for the locations multiplied by the shadow prices for the congested branches.

Note that $PTDF_A$-$PTDF_B$ represents the incremental flow of a 1 MW transaction between hubs A and B on a given critical branch. The PTDF value itself is meaningless. In fact, PTDFs are calculated using a slack hub, and they represent the incremental flow on a given critical branch of a 1 MW transaction between the hub the PTDF value refers to and the slack hub.

In the ATC method, each TSO considered historical data for a reference day, considering loop flows, seasonal impact and security margin, and determined a net transfer capacity (NTC) value for each direction on each border of its control area. NTCs can be viewed as the maximum allowable commercial[1] exchanges that put a critical network element to its maximum physical flow. Neighbor TSOs coordinate bilaterally to agree upon an NTC value predominantly limited by the lower NTC value. From the NTC values, ATC values can be determined by subtracting long term nominations.

In the ATC method the following property holds:

$$P_z - P_y = \mu_{z\rightarrow y} - \mu_{y\rightarrow z}, \tag{8}$$

where $\mu_{z->y}$ is the shadow price of a unidirectional interconnector transporting power from area z to y.

Thus, under FBMC the country price differentials in FBMC are proportionate to the electrical characteristics of the network and that congestion on one border is sufficient to cause price differences in all countries. Conversely, under ATC the country price difference between two countries only depends on the shadow price on the border connecting those countries. Thus, congestion on the various borders is independent.

2.4. Comparison

The advantages and drawbacks of FBMC and ATC approaches are reported in Table 1; losses in both approaches are ignored. The key features of ATC and FBMC are reported in Table 2.

For further information and background on FMBC, see ETSO [12], De Jong et al. [13], Glachant [14] and Van der Berg et al. [4].

5. Results from the parallel runs from 2013 to 2015

Parallel runs of ATC vs FBMC conducted by the CASC from 2013 to 2015, show that social welfare and cross-border flows increased as more capacity was made available to the market. Likewise, cross-border country price differentials decreased. Germany's ability to exported more power supported its domestic prices, whereas Belgium and the Netherlands imported more power which depressed their domestic prices. France experienced a small price decrease. On average, German prices increased by 1.35 €/MWh, Belgian prices decreased by 2.85 €/MWh, Dutch prices decreased by 2.17 €/MWh and French prices decreased slightly by 0.51 €/MWh. The results are reported in Table 3.

Likewise, the cross-border spreads calculated from 2013 to 2015 show that prices decreased the most between Germany and the Netherlands (3.52 €/MWh), whereas they increased between France and Belgium (2.33 €/MWh) and France and Germany (1.86 €/MWh), and slightly increased slightly (0.68 €/MWh) between Belgium and the Netherlands. The results are reported in Table 4; the convention in the table is "source" to "sink".

Some price differentials mathematically increased but only because the price differential for these borders "happened" to be negative.

6. Analytical methods for the flow based market coupling method

In this section we discuss two analytical frameworks for the flow based market coupling method. The first approach utilizes the utility tool published daily by CASC. The second approach utilizes historical analysis of constraints.

6.1. The utility tool

Each day at 8.30 a.m. and 10.30 a.m. on the day before delivery, CASC publishes market and operational information. The online tool's interface allows users to check for different simultaneous cross-border trades. The tool contains ex ante information about the relevant PTDFs and RAMs including maximum bilateral exchanges and minimum

Table 1
Advantages and drawbacks of FBMC and ATC.

	FBMC	ATC
Pros	Higher social welfare as more transmission capacity becomes available More efficient use of the electrical network Coordinated capacity calculation and allocation mechanism Obeys the laws of physics Formulates transmission constraints to reflect the network's physical limitations Larger security domain, i.e., larger set of trading opportunities	Forecasts for longer term transmission capacity are available "Easier" to understand and use
Cons	More complicated analyses of congestion for the day-ahead market More complicated price forecasting for the day-ahead market Trading longer term contracts is more difficult since there is no forecast of future transmission capacity	Lower social welfare as less transmission capacity becomes available Uncoordinated capacity calculation and allocation mechanism Ignores the laws of physics Smaller security domain, i.e., smaller set of trading opportunities

[1] Commercial capacity is the amount of trade that puts a critical network element to its maximum physical power flow. Physical capacity is the amount of power that can flow over an unconstrained line.

Table 2
Summary of the key differences between FBMC and ATC [11].

	FBMC	ATC
Available capacity calculation	Regional coordination among TSOs	Bilateral coordination between TSOs
	Set of critical branches with associated available physical capacity	Commercial capacity (NTC) values for each border direction
Verification	24 time-stamps verified daily	2 time- stamps verified daily
Long term inclusion	Each considered critical branch	Each direction on each border
Capacity allocation	Constraint for each considered branch	Constraint for each direction on each border
	Market based allocation via bids and offers	Capacity predetermined

and maximum net positions. The main page or "Market view" is shown in Fig. 1.

The most important spreadsheets in the Excel file are as follows [15]:

PTDFs_Early Publication: Ex ante PTDF matrix and RAMs for pre-solved critical branches for the next day excluding long term nominations for each single hour
PTDFs: Ex ante PTDF matrix and RAMs for pre-solved critical branches for the next day following long term nominations for each single hour
Max net pos: Ex ante minimum and maximum net positions in each CWE country for the following day; the min/max net positions depend on the net positions of the other hubs. Thus, they are not simultaneously feasible.
Max exchanges (Maxbex): Ex ante maximum bilateral exchanges between each CWE country for the following day assuming that the other net positions are null
Net position: Ex post CWE net positions in MW computed by the market coupling algorithm; published at 1 p.m. the day before delivery
Allocated capacities: Ex post allocated capacities computed from the CWE net positions resulting from the bilateral exchange computation (BEC) assuming the constraint is intuitive; published at 1 p.m. the day before delivery
Price spreads: Ex post market price spread in €/MWh for the two directions; published at 1 p.m. the day before delivery
All CBCO fixed label: Information about the ex post CBCOs used for a particular date with a fixed label; each row provides the features of one CBCO per hour; published two days after the delivery date

"Market view," PTDFs, max net pos and max exchanges (Maxbex) can be used prior to the clearing of the day-ahead market to identify potentially binding constraints. Historical net positions, allocated capacities, price spreads and CBXO fixed labels are retrieved by specifying the date of interest.

An example of the first step in an ex ante analysis include:

In the volume (interactive) module in the "Market view" sheet, the uses can specify hub to hub exchanges or hub positions and check for the date and hour of interest. If the combinations are infeasible, cells will be marked "Constrained Transmission System" in red. Thus, traders can check the simultaneous execution of trading volumes in CWE markets.
In the max volume (information) module in the "Market view" sheet, the user can find the maximal trade volumes (MWh/h) which can be physically transported between two hubs under the condition that no other trade is executed between other hubs.
Are there any changes in maximum bilateral exchanges day on day or similar weekday the previous week? Curtailments in maximum exchanges can lead to congestion on the relevant border with the exporting hub exposed to lower prices and the importing region to higher prices. Conversely, if maximum exchanges increase, it facilitates higher exports with higher prices in the exporting hub and lower prices in the importing hub.

Table 3
Results of the parallel runs ATC vs FBMC for 2013, 2014 and 2015.

		Q1-13	Q2-13	Q3-13	Q4-13	Q1-14	Q2-14	Q3-14	Q4-14	Q1-15	average
ATC	Germany	43.77	32.65	38.26	37.69	33.26	31.38	31.49	34.82	32.11	35.05
	France	54.15	33.56	36.73	48.10	37.58	31.55	28.40	40.89	44.92	39.54
	Belgium	56.34	45.84	38.27	47.54	38.45	39.17	39.02	46.19	46.69	44.17
	Holland	54.54	52.10	48.49	52.10	42.82	38.61	38.65	44.37	43.01	46.08
FBMC	Germany	46.03	33.72	38.81	39.81	34.15	31.79	32.28	36.51	34.47	36.40
	France	51.09	34.69	36.86	46.54	37.05	32.92	29.65	39.96	42.50	39.03
	Belgium	54.07	40.97	37.33	46.27	38.11	34.72	34.13	42.08	44.19	41.32
	Holland	55.06	47.90	46.52	48.76	40.55	35.85	36.44	42.16	41.95	43.91
Delta	Germany	2.26	1.07	0.55	2.12	0.89	0.41	0.79	1.69	2.36	1.35
	France	−3.06	1.13	0.13	−1.56	−0.53	1.37	1.25	−0.93	−2.43	−0.51
	Belgium	−2.27	−4.87	−0.94	−1.27	−0.34	−4.45	−4.89	−4.11	−2.50	−2.85
	Holland	0.52	−4.20	−1.97	−3.34	−2.27	−2.76	−2.21	−2.21	−1.06	−2.17

Table 4
Cross-border spreads of the parallel runs ATC vs FBMC for 2013, 2014 and 2015.

		Q1-13	Q2-13	Q3-13	Q4-13	Q1-14	Q2-14	Q3-14	Q4-14	Q1-15	average
ATC	BE-NL	−1.80	6.26	10.22	4.56	4.37	−0.56	−0.37	−1.82	−3.68	1.91
	DE-NL	10.77	19.45	10.23	14.41	9.56	7.23	7.16	9.55	10.90	11.03
	BE-FR	−2.19	−12.28	−1.54	0.56	−0.87	−7.62	−10.62	−5.30	−1.76	−4.62
	FR-DE	−10.38	−0.91	1.53	−10.41	−4.32	−0.17	3.09	−6.07	−12.81	−4.49
FBMC	BE-NL	0.99	6.93	9.19	2.49	2.44	1.13	2.31	0.08	−2.24	2.59
	DE-NL	9.03	14.18	7.71	8.95	6.40	4.06	4.16	5.65	7.48	7.51
	BE-FR	−2.98	−6.28	−0.47	0.27	−1.06	−1.80	−4.48	−2.12	−1.69	−2.29
	FR-DE	−5.06	−0.97	1.95	−6.73	−2.90	−1.13	2.63	−3.45	−8.02	−2.63
Delta	BE-NL	2.79	0.67	−1.03	−2.07	−1.93	1.69	2.68	1.90	1.44	0.68
	DE-NL	−1.74	−5.27	−2.52	−5.46	−3.16	−3.17	−3.00	−3.90	−3.42	−3.52
	BE-FR	−0.79	6.00	1.07	−0.29	−0.19	5.82	6.14	3.18	0.07	2.33
	FR-DE	5.32	−0.06	0.42	3.68	1.42	−0.96	−0.46	2.62	4.79	1.86

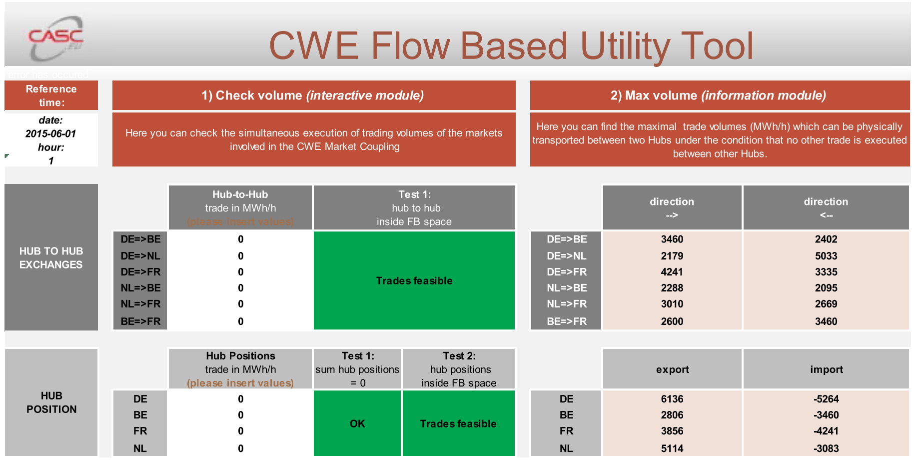

Fig. 1. CASC's utility tool.

Are there any changes on minimum and maximum net positions? A higher minimum or maximum net position indicates a better supplied hub. Conversely, a lower maximum or minimum net position indicates a more strained supply-demand balance.

After obtaining this information, the second step is to reduce the number of potentially binding RAM constraints, considering:

Exporting country: Constraining critical branch with PTDF >0
Importing country: Constraining critical branch with PTDF <0
Low RAM value indicates a higher probability of congestion and price decoupling

Country net positions are the inputs in the RAM constraints. Thus, the starting point is a view on the supply-demand balance in each CWE country. The net position, defined as supply minus demand for each country, indicates the degree of tightness in the relevant country. A country with little tightness has surplus power for exports, i.e., a positive net position and a country with a high degree of tightness has a deficit, i.e., a negative net position. The net position for a country equals the sum of country export minus imports and long-term nominations to/from other CWE countries. After analyzing the supply-demand balance in each CWE country, the number of potentially binding constraints can be reduced. Countries with deficits should consider negative PTDFs and countries with surplus should consider positive PTDFs. Constraints with the highest RAM can be excluded since they are not likely to be binding.

The final step is to test the feasibility of various net positions if they do not violate any transmission constraints. If there are no violations, it is likely that prices will couple in those hours, whereas if constraints are violated, prices will decouple in those hours. The recent net positions give indications of the present tightness in the country.

Alternatively, a user can build a simulation tool with a social welfare objective, given expectations about the hourly country prices and RAM constraints including PTDFs. Country net positions are the decision variables. This alternative tool allows the user to identify the binding constraints, given country price expectations and determine the hours when prices decouple.

6.2. *Historical analysis of binding constraints*

It is also useful to track the history of active constraints. CASC publishes active constraints two days after delivery. The numerical code differentiating the various border/countries, is retrieved from the two first numbers in the ID of the relevant constraint [15] as shown in Table 5.

Each day at 1pm on the day before delivery, CASC publishes the net positions. The active constraints can be identified by inserting the hourly net positions for each country in eq. (4). If the left-hand side is greater than or equal to the right-hand side, the constraint is active and binding, i.e., the actual PTDF values for active constraints are identified. When multiplied by the respective net positions, the congested hub and the cause (import or export) of the congestion is identified.

However, two days ex post, the actual congested borders or locations can be identified. Some constraints may span over several days. By keeping a record of the active constraints, a user can generate useful statistics about the most common cross-border congestion constraints.[2]

7. Flow based market coupling results from the operational runs

Average cross-border spreads from May 21, 2015 to March 31, 2016 are listed in Table 6. Compared to the full parallel run analysis period, prices decreased for the Belgian-Dutch border, the Belgian-French border and the French-German border and increased for the German-Dutch border prices. The most congested borders were the French-German border and the Belgian-Dutch border. The price duration curves are illustrated in Fig. 2.

Monthly cross-border spreads for the same time period are listed in Table 7. The largest spreads in the winter months were French-German

Table 5
Codes for borders/countries in the CWE region.

Code	Border/Country
11	BE
12	BE-NL
13	NL
14	NL-DE
15	DE
16	DE-FR
17	FR
18	FR-BE

[2] It is useful to study locational marginal pricing markets in the United States when building historical transmission congestion databases. This analytics framework could include the following [16]: 1) Transmission map highlighting key transmission lines, interfaces, etc., 2) Identification of flow directions based on historical prices, 3) Identification of historical bottlenecks, 4) Database of real time and day-ahead prices, shadow prices, congestion, etc., 5) Digital map or contour map showing different variables (prices, congestion, outages, etc.) stored in database mentioned in 4., 6) Monitoring every market constraint and explanation (self-analysis; media coverage; system and transmission operator reports).

border and the Belgium-Dutch border. The largest spread from August to October was the Belgian-French border when the outage of several nuclear plants caused a tight supply situation in Belgium. The largest spread in the summer months June to August was the German-Dutch border when Dutch prices were supported by the same tight supply situation in Belgium. The most frequent congestion was the German-Dutch and the Belgium-Dutch borders.

Net positions for the CWE countries are listed in Table 8. Germany was a net exporter because it had vast amounts of renewables. Imports to France were higher in the winter months. France exported more in the summer months when demand was low. Belgium and the Netherlands imported on average in all months.

8. Implications for traders

The introduction of FBMC has led to a change in trading patterns. Moreover, CASC only issues the utility tool twice for the day-ahead market. The only change observed between the 8.30 a.m. version and the 10.30 a.m. version is the inclusion of long term nominations. Without price driving information at 10.30 a.m., traders cannot anticipate the future PTDFs, maximum bilateral exchanges and minimum/maximum net positions. Over time, it can be assumed that tech-savvy traders will be hired or educated, so that FBMC will be well-understood.

For the day-ahead market, traders may utilize information about maximum bilateral exchanges from the utility tool published ex ante. An increase in maximum bilateral exchange indicates a likelihood of decreased country price differential as the price in the exporting country increases and the price in the importing country decreases. Conversely, a decrease in maximum bilateral exchange indicates a likelihood of increased country price differential as the price in the exporting country decreases and the price in the importing country increases. It is also useful to study the daily or weekend to weekend change in the early publication PTDFs from the utility tool. An increase in the PTDF differential indicates the likelihood of higher country price differentials, whereas a decrease in the PTDF differential indicates the likelihood of lower country price differentials.

Trading contracts beyond the day-ahead market is very complex in FBMC. For example, highly inter-related flows require studying the entire CWE region in depth. Chantelou [17] questions whether PTDFs and RAM can be translated into simpler metrics to evaluate the level of transmission constraints and represent the effects of FBMC in a fundamental market model. FBMC's constraints define a feasible security domain for flows within CWE [17]. This domain may be viewed as a volume in the space of net positions by three of the four CWE countries.[3] The domain is characterized by the CWE flow-based volume which indicates the level of transmission congestion, i. e., the lower the volume, the more constrained the system. Additionally, the CWE flow based import/export volume can help traders understand where FBMC's constraints are most binding in the space of net hub positions. For each country, the sum of export and import quadrant volumes equals the total volume. It is possible to compare two domains by calculating the distance between them as specified by the volume of space which is included in only one of the domains. Chantelou [17], who states that the FBMC security domain is only one factor to consider when looking at prices in the CWE region, defines a convergence metric as the sum of the absolute price difference between a specific CWE country and the other CWE countries. The metric only indicates the level of electrical network constraints. FBMC's domain volume explains convergence only partially because of the effects of other market fundamentals.

Modelling FBMC's market fundamentals in the medium/long term will require anticipating FBMC's constraints beyond the day-ahead [17], and developing a fundamental model of the entire CWE region and the possible flows that can be limited by FBMC's constraints.

It may be possible to apply constraints from a similar day in the past to model the future, after formally defining “similar” from the perspective of FBMC perspective. Chantelou [17] suggests consumption, solar generation and wind generation in France, Netherlands, Belgium and Germany, and wind generation in the four German TSO zones as variables.

Table 6
Cross-border spreads of FBMC from May 21, 2015 to March 31, 2016.

	Border	Average	Total number of congested hours
FBMC	BE-NL	−3.85	1808
	DE-NL	5.25	4468
	BE-FR	−4.80	1083
	FR-DE	−4.30	601

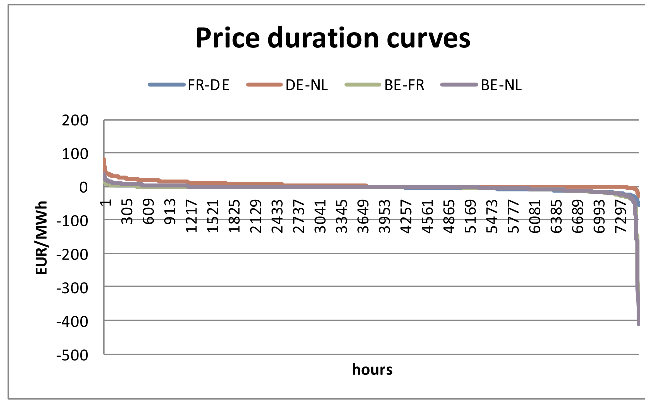

Fig. 2. Price duration curves from May 21, 2015 to March 31, 2016.

Table 7
Monthly cross-border spreads of FBMC from May 21, 2015 to March 31, 2016.

Month	BE-NL	DE-NL	BE-FR	FR-DE
May-15	1.14	5.11	−3.20	−0.77
Jun-15	−0.26	8.68	−6.90	−2.04
Jul-15	−0.47	7.14	−4.65	−2.96
Aug-15	−3.52	7.29	−10.27	−0.54
Sep-15	−12.84	7.80	−15.08	−5.56
Oct-15	−14.03	2.08	−10.49	−5.62
Nov-15	−4.64	6.07	−1.42	−9.29
Dec-15	−2.25	5.95	−0.81	−7.38
Jan-16	−1.04	2.54	0.99	−4.57
Feb-16	−0.18	3.20	0.14	−3.52
Mar-16	−0.99	1.86	−0.03	−2.81

Table 8
Monthly net positions for Germany, France, the Netherlands and Belgium from May 21, 2015 to March 31, 2016.

Month	DE	FR	BE	NL
maj-15	2627	1401	−1258	−2771
jun-15	2167	1528	−1633	−2062
jul-15	1027	1974	−2013	−988
aug-15	1110	2331	−2127	−1314
sep-15	1696	152	−1628	−220
okt-15	1914	−223	−1667	−25
nov-15	2722	−852	−1339	−531
dec-15	3316	−1459	−1326	−531
jan-16	2630	−1571	−58	−1001
feb-16	3663	−1698	−601	−1364
mar-16	3096	−1604	−374	−1117

[3] The net position of the fourth country can be expressed as the sum of the other three countries.

9. Conclusions

This paper discussed the mathematical formulation and parameters of the flow based market coupling method (FBMC) implemented on May 21, 2015 in the CWE region. Initially, a cross-border trade in the CWE region involved separate auctions of energy and transmission capacity. However, if the market participants' price expectation was incorrect, flows could move from a high price area to a low price area. To address the problem, implicit auctioning, where energy only was traded in the day-ahead market, considering the electrical characteristics of the network was implemented. FBMC uses the electrical network's physical transmission constraints and allocates cross-border flows, considering the PTDFs, which provides sensitivity information about a change in import/export at any particular hub or country. The country price differentials in FBMC are proportionate to the network's electrical characteristics, and congestion on one border is sufficient to cause price differentials in all countries. The merits of FBMC have included higher social welfare, efficiency, coordinated capacity calculations, electrical representation of the network and a larger set of trading opportunities.

Parallel run results and operational results from the flow based market coupling between 2013 and 2015 were analyzed. Among the findings, cross-border country price differentials decreased as exports and imports rose because of increased cross-border capacity. German prices increased, whereas Dutch and Belgium prices decreased. The result was lower German-Dutch price spreads but higher French-Belgian and French-German price differentials. The most frequent congestion was the German-Dutch and the Belgium-Dutch borders. However, French-Belgium congestion gradually decreased as the supply situation improved.

Two possible online tools for use by traders to take full advantage of FBMC were suggested. Both tools require extensive analytical and forecasting ability. CASC's online utility tool is presently available only for the day-ahead market, and trading contracts beyond the day-ahead market requires studying the entire CWE region. The other tool involves constructing, and updating, a model of real time and historical data in spreadsheets and other electronic formats to help traders identify trends and forecast potential congestion trouble spots.

In conclusion, the flow based market coupling mechanism, while more demanding to use, leads to higher social welfare and cross-border flows than the simpler ATC model. However, if transmission system operators continue to only publish forecasts of power transfer distribution factors for the day-ahead market, traders will find it difficult to forecast prices beyond this timeframe.

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