Adequacy Study CWE

4th November 2014

Contents

1 Introduction

CWE NRAs requested the project to study if a link exists between market coupling under FB and short term generation adequacy. This report studies that link, focussing in particular on the Belgian market and its ability to import. The expected scarcity situation and the fact that Belgium has no other electrical borders outside CWE explain this particular focus. The report explores

- The theoretical impact FB capacity allocation can have on adequacy;
- Quantitative results of these effects for the Belgian market;
- Potential mitigations to be assessed for any adverse effects, both from a TSO operational perspective as well as suggested changes of dealing with "price taking" orders in the respective DA markets;

2 Conceptual approach

The object of this study is the special situation where available supply is insufficient to meet all demand at the DA stage. If closer to real-time this situation cannot be restored this may in some extreme cases result in shedding of load. Indeed, it is not because one observes price caps or even order curtailment on the spot market that this will necessarily bring about issues in terms of physical delivery. The focus of the study is supply inadequacy at the DA stage, and the differences in assigning scarce resources between FB and ATC. This chapter better explains the differences between FB and ATC, and reminds why this situation is more relevant this winter than others.

2.1. Different order curtailment risk in FB MC than in ATC MC

Since the purpose of this work focuses on scarcity situations where not all demand can be satisfied, this suggests in DA we are in an order curtailment situation: part of the price taking demand orders (buy orders submitted at the maximum price, currently set at 3000€/MWh in the MRC region) cannot be fully matched. To better understand this situation we consider the order curtailment rules implemented in the Euphemia algorithm that couples the MRC markets. Details are provided in section 7.1.

The principle behind the order curtailment rules is to try to equally share the scarce resources amongst the different areas. If two or more areas simultaneously find themselves in an order curtailment situation (i.e. clearing at 3000 €/MWh), the available supply is pro-rated over the countries, to the extent network constraints allow this.

In Euphemia this is implemented as a post-processing step: once a welfare maximising solution has been found, Euphemia inspects whether an order curtailment situation involving two or more areas occurs. If it does, a subsequent step follows to ration the scarce supply to the extent network constraints allow this. This step does not change the DA market welfare: some of the energy bought at 3000€/MWh in area A is funnelled to hub B, where it is also bought at 3000€/MWh. The net effect is naught on the DA market welfare, but there is a physical impact for the curtailed hubs.

One of the key characteristics of FB allocation is that the selection of the accepted/matched deals is influenced by the impact that the deals have on the physical elements of the grid (modelled by the PTDFs). If two possible deals generate the same welfare, the one having the lowest impact on the scarce capacity will be selected. It also means that, in order to optimize the use of the grid and to maximize the market welfare, some sell (/buy) bids with lower (/higher) prices than other sell (/buy) bids will not systematically be selected with Flow-Based allocation. This is a well-known and intrinsic property of Flow-Based sometime referred to as “flow factor competition”. In ATC market coupling, a sell bid in one market area is simply sold to the buyer out-pricing all other buyers. In FB market coupling, out-pricing other buyers is not sufficient to get the deal: the localization (bidding area) of the seller and of all possible buyers plays a crucial role.

In case of stressed situations, this can lead to increased price peaks in an importing area: to ensure the imports, the buyers of one particular importing area may have to pay (much) more than buyers in other market areas if the impact of this particular import on the grid is bigger (if the scarce capacity on the critical branch is more heavily consumed by this particular import). This is not an issue as it optimizes the market welfare.

But it becomes an issue if the situation is exceptionally stressed because of scarcity, in one particular zone. Then, this “flow factor competition” could lead to order curtailment. It means that some buyers ready to pay any price (but unable to properly express this due to the price caps in the DA market) to import the energy would be rejected while lower buy bids in other bidding areas are selected. Some “price-taking orders” (buy orders capped at maximum price) in one bidding area are not selected while lower buy orders in other bidding areas are. This would lead to the difficult situation where one bidding area is curtailed while the clearing prices in the other bidding areas are lower. This situation is not possible in ATC market coupling where the energy goes to the buyers ready to pay the higher price. In FB, market players wanting to buy irrespective of the market clearing price could still “lose” the import competition (against others buyers paying less) because their orders are capped at maximum price. In section 3.3 we introduce a model to model this effect. On the basis of simulation results obtained using this model, we try to quantitatively assess this effect.

2.2. Possible impact of order curtailment on Belgium => rolling load shedding concept

An order curtailment situation in a bidding area means that the balance between demand and offer in a bidding zone could not be reached with the long term and day-ahead markets. Other means are still available to reach this balance, like intraday and balancing markets, activation of strategic reserves and all inter-TSO actions that can still be undertaken to face these exceptional situations.

For the coming winter, if Belgium cannot cover its consumption needs with these different means, there will be a power shortage. Elia has to inform the authorities if there is a risk of a power shortage for some hours and authorities are then responsible for deciding to limit electricity consumption. Planned outages (namely, controlled power cuts in specified areas) can be applied as a last resort to avoid a major imbalance that could result in the collapse of the Belgian and European grids (a black-out).

As part of the Load shedding plan (set down in a Ministerial Decree), a list of high-voltage substations that would have their power cut has been communicated. Selective power outages make it possible to substantially reduce consumption at a critical point (e.g. at the peak time for power consumption in winter, namely between 5.00 p.m. and 8.00 p.m.) by cutting the power supply during a certain period to some consumers.

The criteria underpinning the Load shedding plan are 'gradualness', i.e. having multiple tranches that can be activated in response to an incident, the geographical distribution criterion (for dealing with voltage issues and preventing imbalances on the grid), and the order of priority as referred to in the aforementioned Ministerial Decree.

The Belgian Load shedding plan features six tranches. Each tranche corresponds to 500 MW that will be switched off in the event of a planned outage. The tranches are distributed across Belgium's provinces and regions. If there is a power shortage and it looks like the measures designed to reduce consumption will be insufficient, the power supply is cut in a first tranche. This ensures that the grid's stability is not jeopardised. If this is not enough, the power supply in a second tranche is cut too. Each outage will last no more than two to three hours. If outages are required again later on, power will be cut in the other tranches first. A rotation system is in place to make sure that the outages do not always affect the same consumers. This system is also known as “rolling load shedding”.

3 Quantitative assessment

Order curtailment problems in the Belgian DA market can be mitigated if Belgian import can cover at least the difference between the local price taking demand and the total available local supply. Elia did a loss of load expectation calculation for the winter of 2014/2015. In its assessment Elia included an expected BE import of 3500MW. Our assessment will therefore explore to what extent BE can import at least 3500MW under FB, and what the conditions are where they cannot.

We should bear in mind that the 3500MW value is not a guaranteed value, neither under ATC.

As explained in section 2.1 the order curtailment risk in FB potentially increases as a side effect of welfare optimisation, namely “flow factor competition”, which is new compared to ATC. In section 3.3.1 we suggest a modelling approach aimed to capture precisely that.

3.1. Input data

A Belgian scarcity situation will surely be reflected in the different input parameter of the D-2 capacity calculations (e.g. D2CF, etc.). Ideally a study on adequacy would be based on inputs accurately reflecting such situations. Unfortunately our means to provide such inputs are limited. Instead the data underlying the quantitative analysis are the FB parameters of the parallel run. The upside is this means we have a large dataset that is readily available. The downside is that a scarcity situation is not reflected in these parameters (the D2CF, CB selection and the associated CO and RA do not represent a scarcity situation in FR and BE), making it rather challenging to draw concrete conclusions in terms of adequacy for BE.

The data used for our study considers the parallel run data beginning of 2014 until 30 September. Please note that this data does not correspond to a winter only date set. Even if we would have limited the analysis to the period January to February (meteorological winter), this still would be biased due to the very mild temperatures of winter 2014.

3.2. Import potential and realized imports

To assess whether BE can meet its 3500MW import target under FB, we first consider the maximum BE import.

Figure 1 illustrates what the maximum import represents: it considers a far corner of the FB domain, corresponding to the red dashed rectangle. Due to energy conservation (sum of net positions is zero), maximum imports are not simultaneously feasible, but rather make assumption on what adjacent markets do like in ATC.

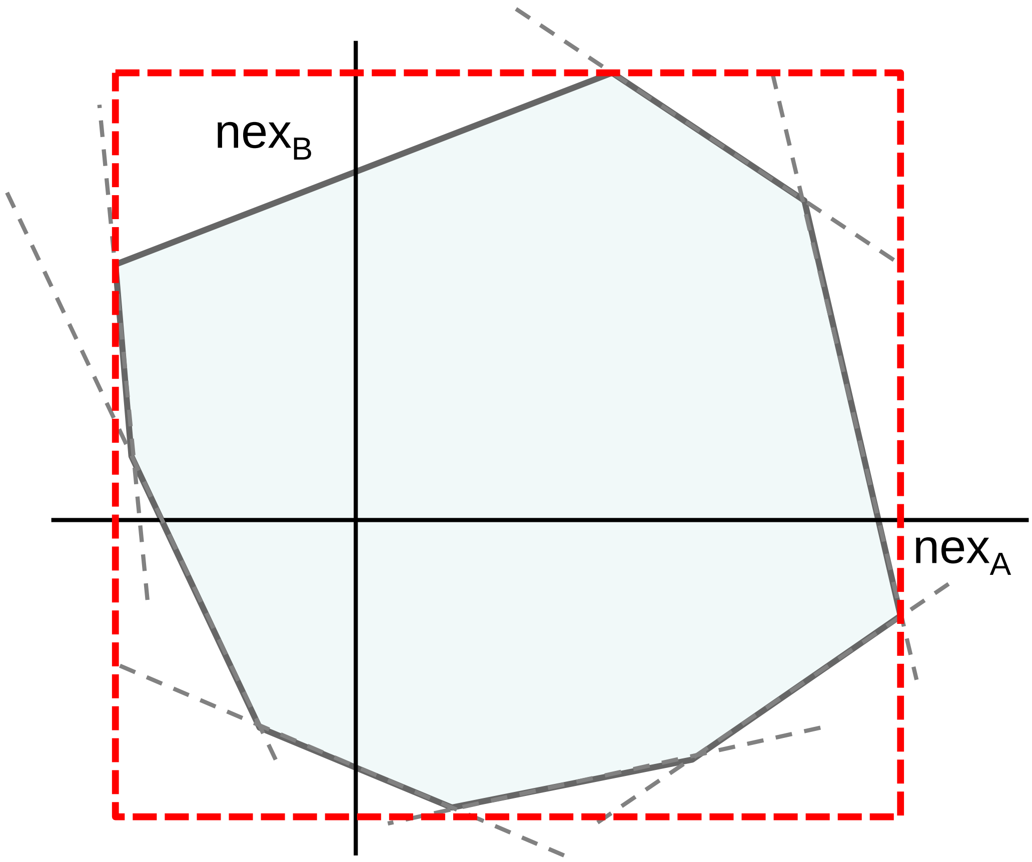

Figure 1 Illustration of max import / export: the far edges of the rectangle containing the FB domain correspond to what a market can import / export at most.

In Figure 2 the maximum import (and export) for BE for hour 12 is illustrated for both FB and ATC constraints. With few exceptions more import is feasible under FB. Under ATC these imports are simultaneously feasible, and no assumptions on adjacent net positions need to be made for the capacity to be there. This assertion should however be nuanced, as under ATC, all configurations are not possible, some combination of NTCs being physically impossible. The “double BE export” is the most famous unlikely corner, but there are other impossible combinations[1]. The parallel run results for BE (added in Figure 4) show that the maximum import under FB is rarely reached. The realized imports under FB do frequently exceed what was possible under ATC.

With the few exceptions where FB offered less import potential than ATC, results suggest that under FB the Belgian market would be better served in a scarcity situation.

Since in the period of the parallel run we did not observe an extremely scarce situation in BE leading to order curtailment, the parallel run results only learn us so much. In the next section we explore in some more detail this scarcity situation.

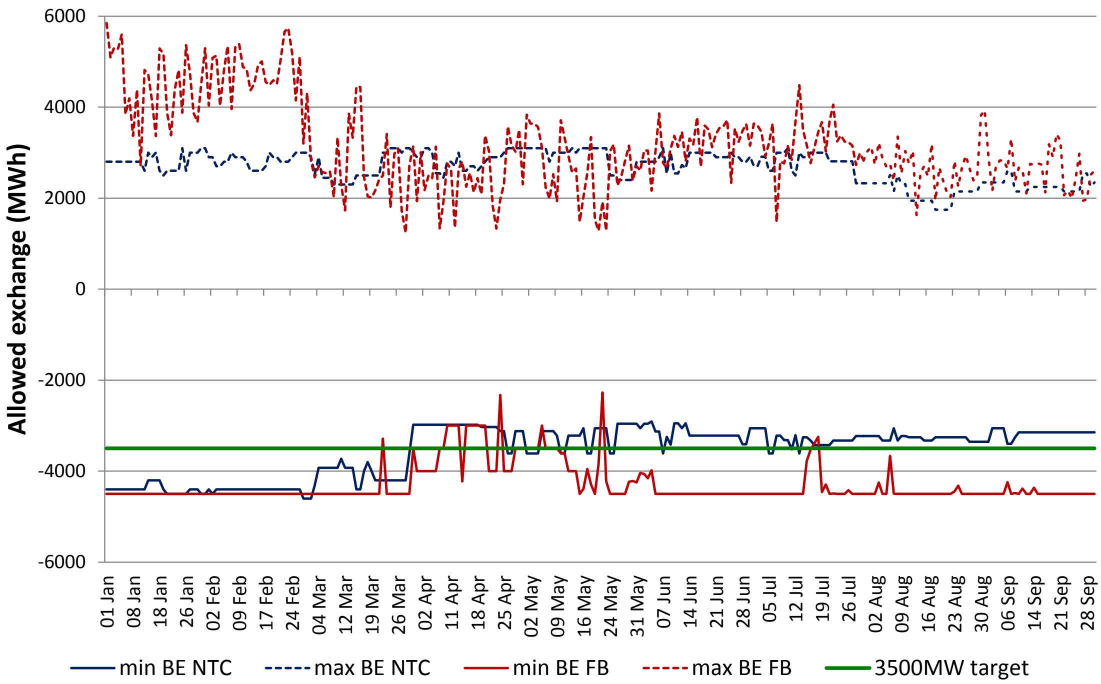

Figure 2 max import / export BE for hour 12

Another way to compare the import potential of ATC and FB is to draw the statistical distribution of the difference (|min BE FB| – |min BE ATC|) over the external parallel run period, i.e. the difference between the red and blue lines of Figure 2. The resulting histogram is provided in Figure 3.

[1] In order not to unnecessarily limit the exchanges on individual borders, TSOs will provide some NTCs that are only individually feasible, considering that their simultaneity is physically impossible.

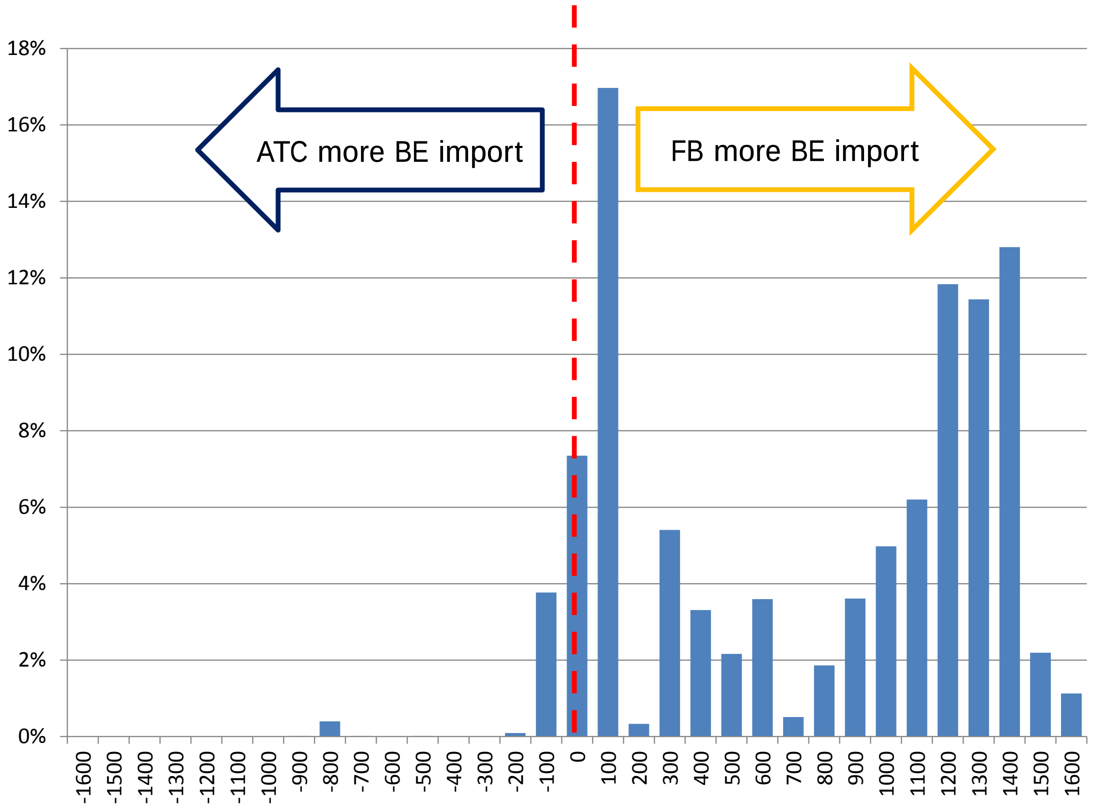

Figure 3 Histogram of the differences in BE import potential between FB and ATC

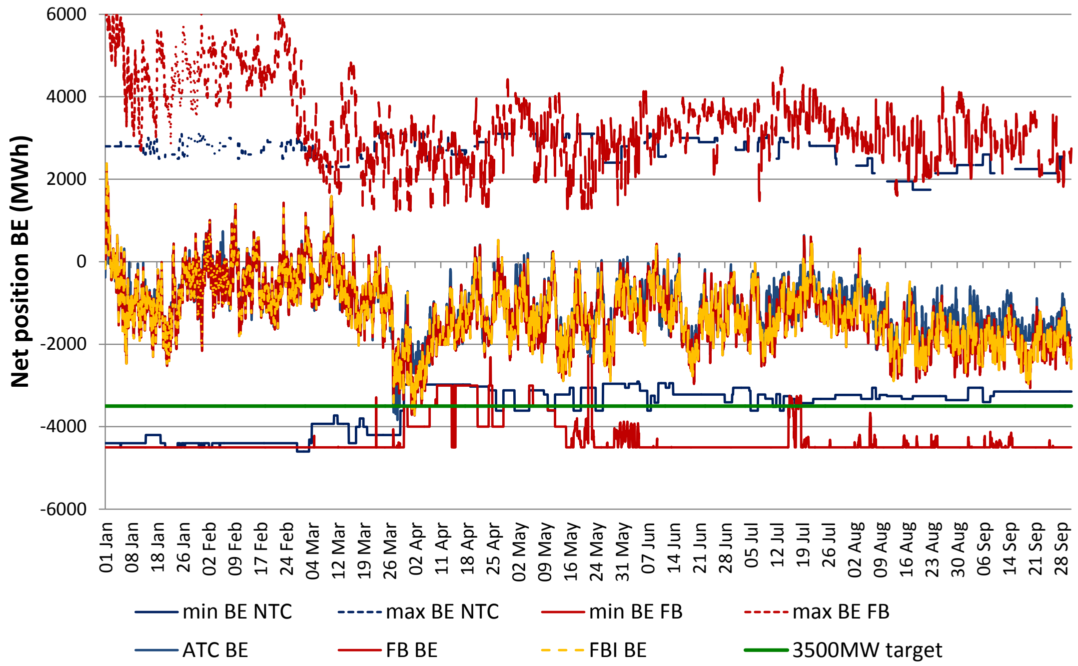

Figure 4 same as Figure 2, now for all hours. The FB/FBI/ATC parallel results are illustrated too.

Another way to visualize the realized imports in ATC and FB is to draw the statistical distribution, over the same period as above, of the difference (NP BE FB – NP BE ATC) when BE is importing (94% of the time-stamps).

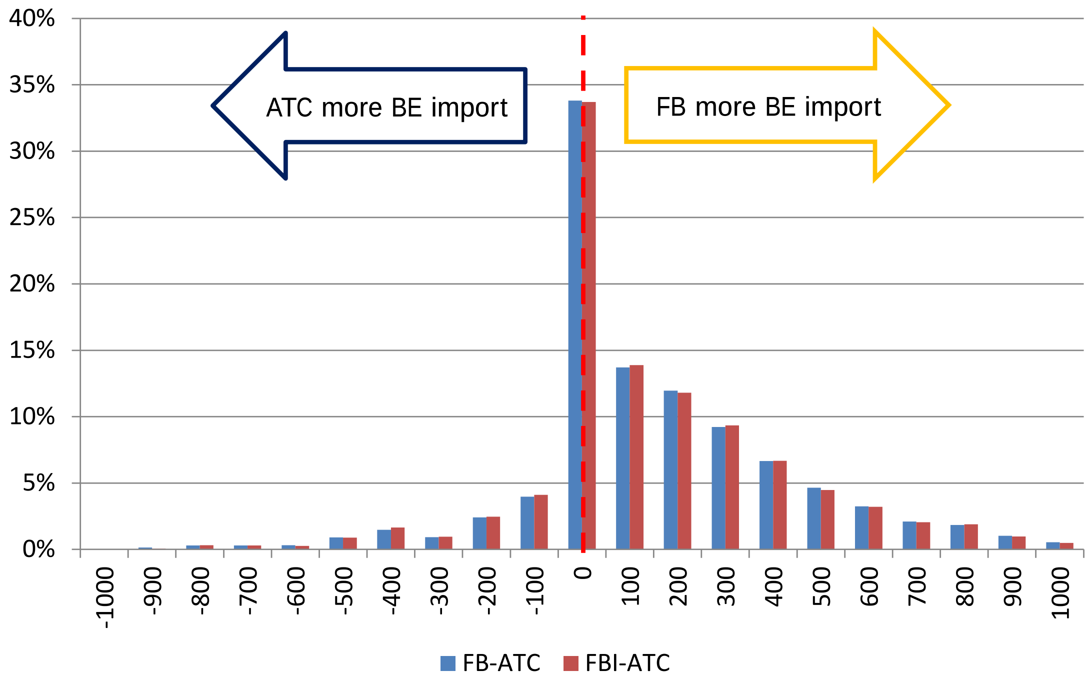

Figure 5 Histogram of the realized Belgian imports under the parallel run: difference between FB and ATC

We observe during this period that the average FBI – ATC realized import was of 155 MW.

3.3. Interaction order curtailment and "flow factor competition"

In the preceding section we only modelled the FB domain itself, but did not factor in order books under scarcity. In this section we want to focus on the special situation where BE faces a scarcity situation resulting in an order curtailment situation. Therefore throughout this section we assume the BE market clears at 3000 €/MWh, the current maximum price in MRC.

3.3.1. Modelling with fixed prices

To assess the max import for BE under a fixed price scenario, we consider a model where we can make assumptions on prices for all CWE area. To make a-priori assumption of the prices, we assume markets which are perfectly elastic: no amount of import or export can change the price. Recall that the objective function to maximise welfare can be written as the sum of buyer and seller surplus plus congestion rent. If we assume perfect elasticity, it means all market clear at their fixed marginal prices, resulting in zero surplus. Therefore in this naïve model the objective function is equivalent with maximising congestion rent: each additional MW that can be exchanged will create a positive contribution to this objective function. More details on the model are provided in section 7.2.

By fixing the BE price to 3000€ and setting the prices of adjacent areas to lower values we would expect BE to import up to its max potential. In fact under ATC this is precisely what will happen. Due to the “flow factor competition” element explained in section 2.1 under FB this is not necessarily the case.

We consider three scenarios, all of which assume BE to clear at 3000€, DE to clear at 50€, NL to clear at 100€. These prices will ensure DE and NL to function as the export hubs. The variable factor will be the price for FR, which will vary between 500€, 1500€ and 2500€. The rationale is that high load in BE during the winter is correlated to a cold spell, which in turn is an excellent proxy for high prices in FR. I.e. BE and FR will be competing for the import from DE and NL. Results are presented in the figures below, by illustrating the BE import under the different scenarios[2]. Note that the full BE net positions are illustrated, i.e. the simulated BE DA net positions plus the LT nominations applicable for that day. Results are aggregated from an hourly resolution to a daily one by showing only the maximum hourly value (worst case) per day.

[2] The peak for May 21st is explained by the fact that the qualification for this day was not properly done (see explanations published on CASC website : http://www.casc.eu/en/Resource-center/CWE-Flow-Based-MC/Parallel-Run-Results)

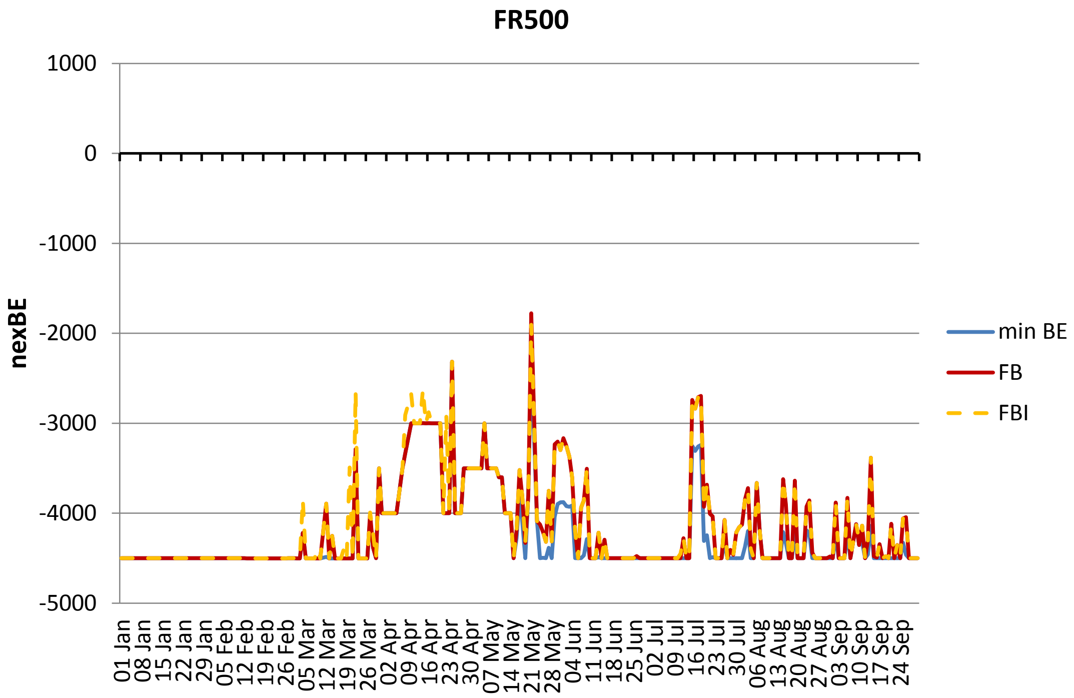

Figure 6 modelled BE net positions in scenario where FR clears at 500€

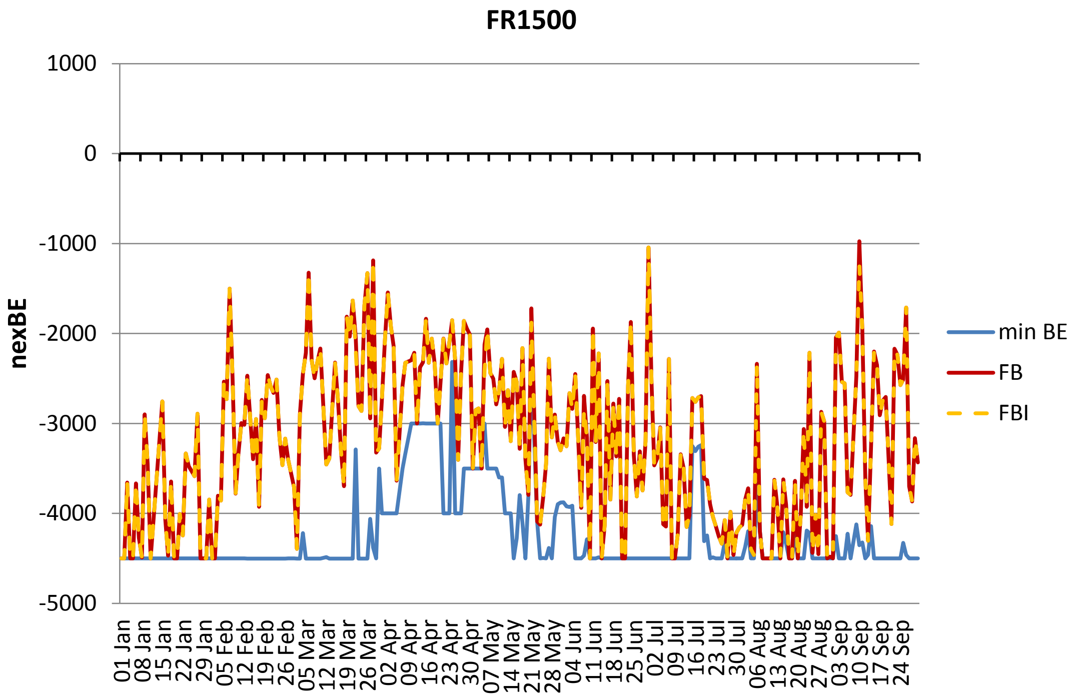

Figure 7 modelled BE net positions in scenario where FR clears at 1500€

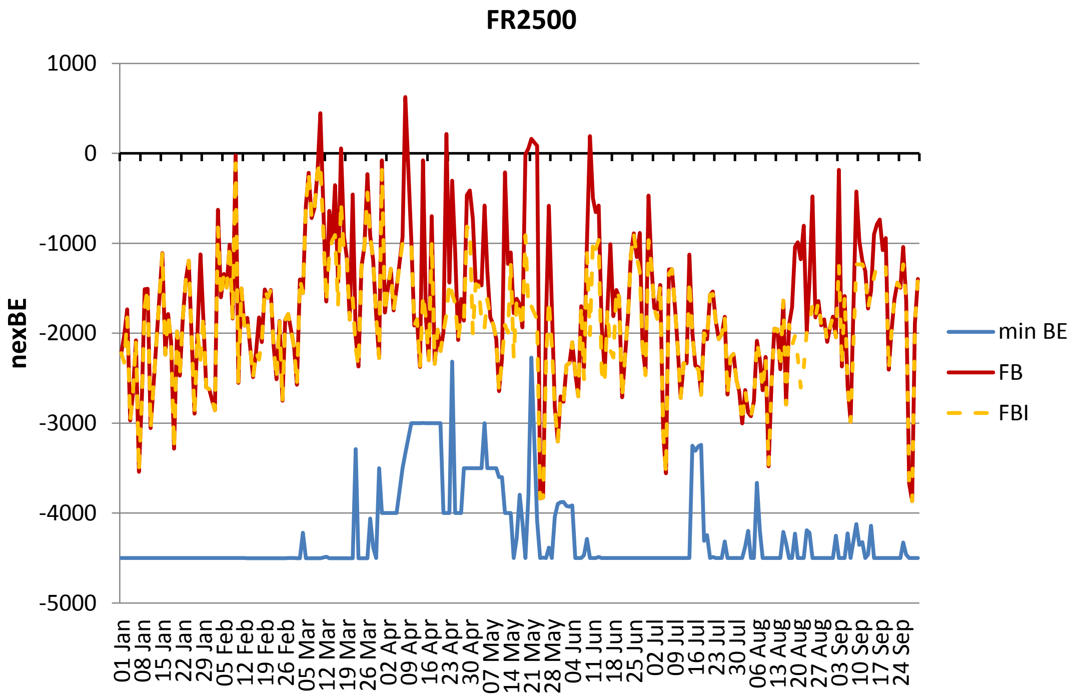

Figure 8 modelled BE net positions in scenario where FR clears at 2500€

In the scenario where an FR price of 500€ is assumed (Figure 6) the differences between the new results and the ones from section 3.2 are minimal. However the subsequent scenarios demonstrated that the risk presented in section 2.1, namely that “flow factor competition” could results in BE order curtailments is not imaginary, but could materialise, assuming that the FB parameters used as inputs for the model are representative of the scarcity situation above: for some of the days in the scenario where FR clears at 2500€ (Figure 8), under the “plain” FB configuration the Belgian market is in fact forced to export, to the detriment of local buyers willing to pay 3000€.

Interpretation

In section 3.1 we already explained that the data for the parallel run is not representative for scarce situation, which remains one of the big caveats since we do not observe the activation of CBs normally involved in high FR import situation (c.f. section 3.4). However the results presented above also need some cautious interpretation: some BE imports are reduced, because on one of the constraining CBs the FR import was more favourable. However in reality assuming a French price of 2500€ is no longer realistic if simultaneously the simulation results suggest FR to import 7000MW on CWE only. Indeed, the experimentations carried on the cold spell of February 2012 9th for instance displayed, under FBI, a French NP of -4200 MW for a price of 1000€, and in actual ATC MC the price of 2000€ was reached with an import of 3600 MW. Therefore for BE import we can at best indicate an interval which is somewhere between the figures of this section and the previous. This range is illustrated in Figure 9 and complemented with the maximum BE import under NTC.

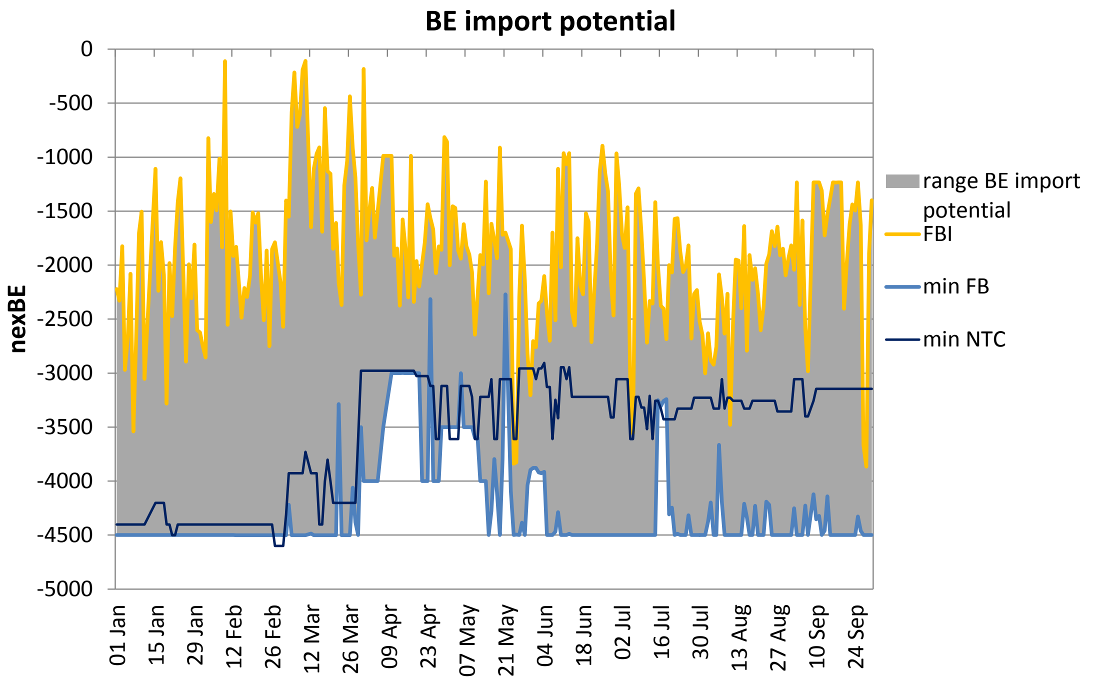

Figure 9 Range of modelled BE import potential (lower, or more negative values correspond to more import)

Alternatively we can also consider the FR net positions simultaneously with the BE ones:

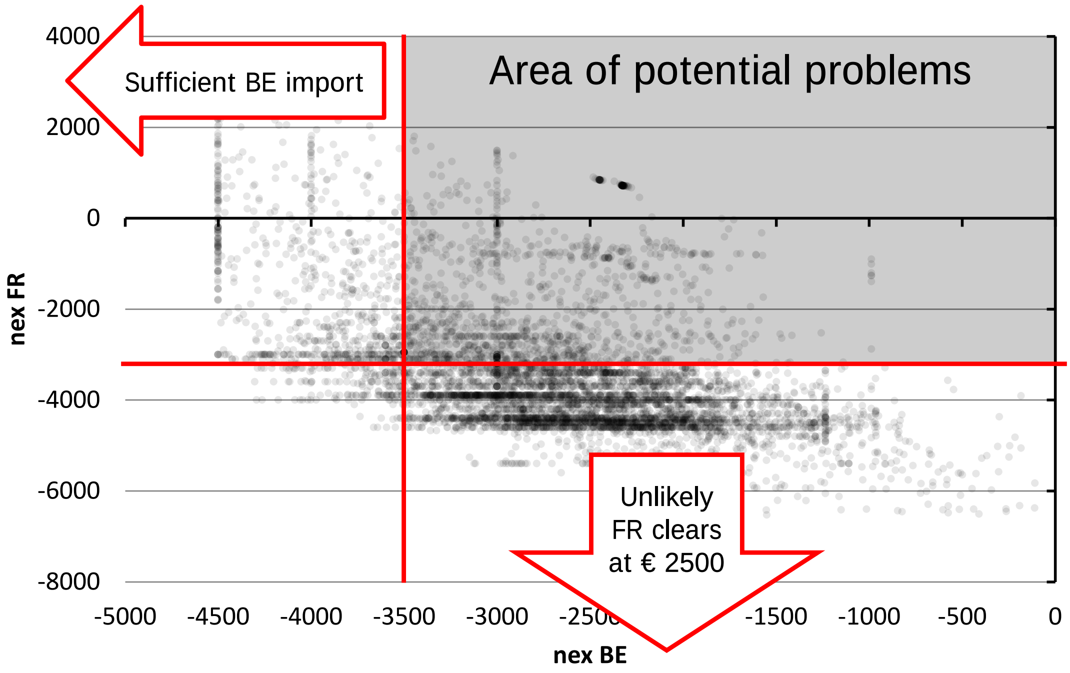

Figure 10 Scatter of BE vs FR net positions under the model where FR is assumed to clear at 2500€.

Figure 10 illustrates that under the scenario where FR clears at 2500€/MWh there exist a number of hours for which the BE import exceeds the 3500MW, which Elia used in its loss of load expectation. There are also hours where the French net position exceeds 3600MW, which is considered too high import to be still compatible with the presumed 2500€/MWh French clearing price[3]. What remains are a significant number of hours where the BE import is less than 3500MW, whereas the French import is not considered incompatible with a clearing price of 2500€/MWh. If in a real scarcity situation in Belgium such a FB domain would result there exists a risk that BE import is reduced compared to what is allowed today under ATC.

3.4. Statistical analysis active CBs

The results of the simulation with the French price at 2500 €/MWh were analysed between January, 1st and July, 4th in order to extract the critical branches which limit the model i.e. the active CBs.

[3] Recall that during the cold spell of 9 February 2012 France imported 3600MW and cleared at 2000€/MWh

Top 10 active CBs between January, 1st and July, 4th (4104 hours)[4]

Occurrence	ID	Hub	DE>FR	DE>BE	NL>FR	NL>BE
2687	17275790000	FR	100%	0%	100%	0%
2634	15338750000	DE	100%	100%	0%	0%
1366	11807910000	BE	13%	24%	29%	40%
665	12276260000	BE-NL	11%	24%	15%	30%
537	11703600000	BE	11%	22%	15%	28%
407	11129260000	BE	10%	19%	25%	34%
247	15002840000	DE	4%	2%	8%	6%
242	11286680000	BE	0%	100%	0%	100%
216	15926020000	DE	8%	6%	4%	2%
208	15826020000	DE	7%	8%	1%	3%

For the modelled simulations the average number of active CBs per hour is 3.2 which confirm that the model often reaches one vertex of the Flow Based matrices (cf. section 7.2). On the right side of the table, one can read the average zone-to-zone PTDFs. The constraining CBs for BE competing FR are highlighted in red i.e. the ones with bigger PTDFs for an exchange DE>BE compared to an exchange DE>FR.

These active CBs show that the FB domains used for the simulation are probably not representative of a scarcity situation in France as the qualification has not been done to maximize the FB domain in this market direction. In case of a tense situation in France and with an appropriate qualification step, the French importing CBs would probably show up like the following ones (average zone-to-zone PTDFs from July 2013 until July 2014):

[4] For a better explanation of the references to the CBCOs, consult the explanatory note *"CWE FB MC_Explanation fixed CBCOs_July2014.pdf"*, available on the FTP server in the new folder "PTDF (Fixed CBCO ID)": http://www.casc.eu/en/Resource-center/CWE-Flow-Based-MC/Parallel-Run-Results

ID	DE>FR	DE>BE	NL>FR	NL>BE
17149351000	5.8%	-5.3%	8.2%	-2.9%
17394020000	6.9%	-5.4%	9.2%	-3.1%
17734910000	8.9%	-7.3%	12.4%	3.5%
17641970000	3.9%	-5.4%	6.3%	-3.0%
17655330000	9.4%	-7.4%	13.1%	-3.7%

Therefore, the simulations results depicted above could have been expected: a simulation of scarcity FR+BE is envisaged, but without having FB domains qualified for such situations. As a consequence, the results show that FR hub is getting the biggest share of available imports from the two other hubs.

4 Mitigations to be assessed

In section 2.1 we discussed how “flow factor competition” could result in an order curtailment situation for a given hub, due to a market not being able to out price its neighbouring countries because of a price cap being hit. If the cap price is reached, this situation does not necessarily lead to a load shedding in a specific country (e.g. 19/10/2009 in France) but, within the curtailed demand in the day-ahead spot market, there is a risk of a negative impact on the system adequacy. The “flow factor competition” has true benefits in terms of optimising the day-ahead market welfare in regular situations (looking at the figures of the parallel run) however when it comes to very extreme cases, it highlights the bias introduced by the price cap.

First mitigations that come to mind would be to alter the effect of this cap:

- Either by altering the maximum price in Belgium above 3000€/MWh;
    - Either coordinated in MRC, maintaining harmonized prices;
    - Or by exception for the Belgian market, only during exceptional circumstances;
- By applying the price cap in a post processing phase;
- Implementing a change in the Euphemia market coupling algorithm to explicitly prioritize price taking orders;

The feasibility of these approaches remains to be assessed. We can already point out that the current draft CACM guideline[5] appears incompatible with the idea of exempting markets from harmonizing extreme prices (cf. article 40). Pursuing this idea hence requires making further adjustments to CACM.

[5] http://ec.europa.eu/energy/gas_electricity/electricity/doc/204108-cacm_formal_proposal_for_comitology.pdf

5 TSO operational approach

5.1. Winter overview in CWE

Now that the target go-live of FBMC has been shifted to the end of the winter, CWE TSOs are currently preparing the next winter by putting into place ad hoc operational procedures in order to cope with extreme situations in Belgium. These procedures are not finalized at the drafting of this note and are not directly related to Flow-Based market coupling.

5.2. Assessment of robustness towards FB implementation

Concerning FB parallel run, an off line process is currently being designed: this off-line process aims at evaluating how the Belgium import capacities could be maximized in FB market coupling. Each week, some Coreso operators in cooperation with Elia will identify scarcity days, and will then monitor the limiting elements of the Belgium import, depending on the French level of import as we know that Belgium import is highly correlated to the French import. In case Belgium import is considered too small, CWE TSOs and coordination centers will enquire for optimized Remedial Actions when possible, and also for some exceptional Remedial Actions if needed. An aggregated report will be created after winter to evaluate those results.

6 Conclusions and next steps

This report addressed the adequacy situation under FB market coupling of the Belgian market: to what extent can Belgium generation plus import meet the Belgian load. If we consider the level of available generation as fixed (at least on the short run) this question becomes equivalent to exploring the import potential of the Belgian market.

If it appeared during the parallel run that globally the BE import potential is larger in FB than in ATC and that this bigger potential has actually been realized (with bigger BE import NP in FB), this observation needs to be nuanced by the fact that:

- In any case the import potential remains dependent on the other exchanges
- The so-called flow factor competition is a fundamental characteristic of the FB allocation method that can significantly affect the realization of this potential.

In this respect, a fundamental model has been run and has illustrated this effect of flow factor competition, leading to order curtailment (i.e. full import potential not being fulfilled despite max price hit) of one given hub while others bid at lower prices.

However, one should bear in mind 2 important limitations in the abovementioned model:

- strong assumptions made when running the model (especially the one of elasticity)
- input data (FB domains) not being representative of the simulated scarcity scenario

Consequently, the model results do not provide sufficient ground to conclude on a possible increase or decrease of the adequacy risk in Belgium linked to FB allocation. Indeed, on the one hand the theory (and its numerical illustration via the model) highlights a risk of order curtailment, on the other hand parallel run results display bigger import potentials and realized import net positions for Belgium.

Without rejecting the “flow factor competition” principle of flow-based, several questions have to be studied to possibly mitigate this order curtailment risk:

- Could an increase of the maximum clearing price (price cap) avoid or limit the issue?

- Could the Euphemia DA market coupling algorithm be adjusted to treat price taking orders with preference?
- Could the price cap be applied after an optimization without cap for price-taking orders?

Next steps

- To prepare FB for the winter of 15/16 the above mentioned will be explored in further detail.
- Assessment of the suggested mitigation of section4;
- Continued monitoring of parallel run results, especially for scarcity situations;

7 Annexes

7.1. Order curtailment in Euphemia

The Euphemia public description, available from a.o. http://static.epexspot.com/document/27917/Euphemia%3A%20Public%20description%20-%20Nov%202013, addresses order curtailment rules in section 6.5 as part of the volume indeterminacy sub problem. To better understand the order curtailment rules we repeat them in this annex, omitting some of the intermediary steps that are part of the volume problem.

Recall that order curtailment is the situation where price taking orders (i.e. buy orders submitted at maximum price, or supply orders submitted at minimum price) cannot be fully met. In this text we focus on the situation that not all buy orders can be met.

The stage before entering the order curtailment rules is the welfare maximisation phase: given the orders that are present in the different markets, Euphemia identifies the solution that maximises the DA market welfare (i.e. the sum of buyer and seller surplus and congestion rent). During this phase one additional constraint prevents order curtailment situations to be deteriorated due to coupling of the markets: to the extent that a local market can supply its own price taking orders. This is illustrated in Figure 13 where the dotted line represents the situation where all supply is used to meet local demand.

The additional constraint that is added to the welfare maximisation is to not allow less demand to be matched that can be met locally, i.e. the value of the dotted line. Note that the dotted line only considers hourly orders, not block orders. This is because the block orders have constraints coming from adjacent hours too, so it cannot be a-priori guaranteed that these orders can be activated.

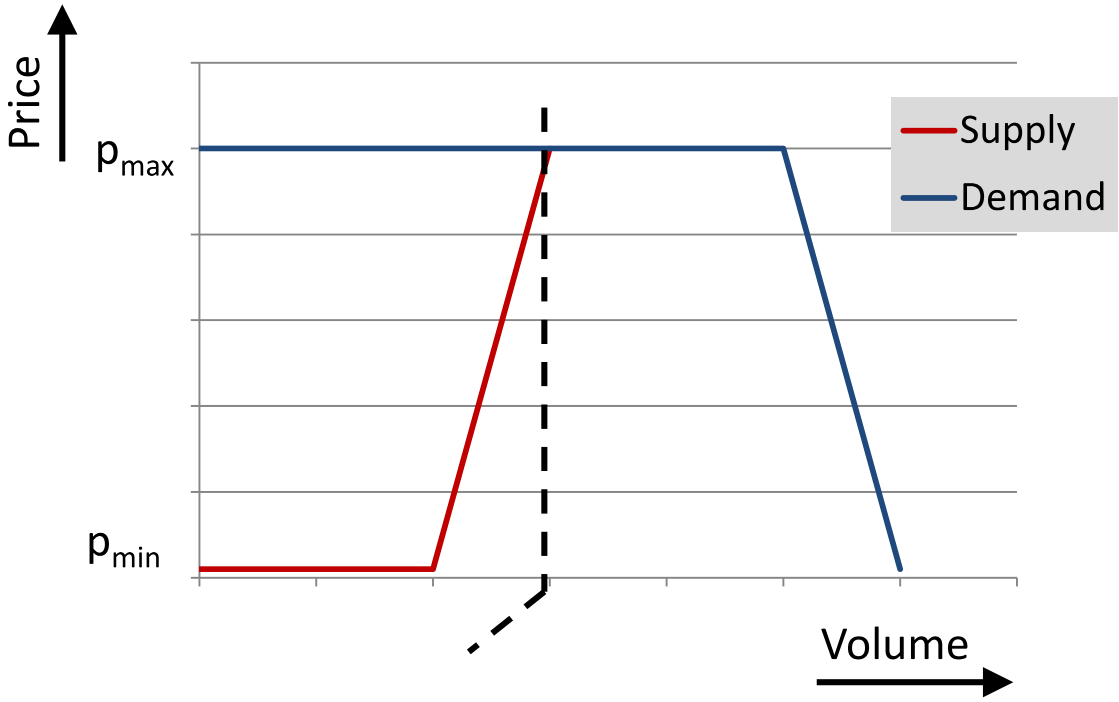

Figure 11 Illustration how price taking demand can be partially matched by local supply (up to dotted line)

Order Curtailment sharing

After the welfare maximisation step a order curtailment sharing step follows. If one or more markets face an adequacy problem, the order curtailment sharing tries to distribute available supply equally amongst the markets in order curtailment. This can be done without impacting welfare: all curtailed orders have been submitted at the maximum price (today in MRC this is € 3000), hence increasing the order curtailment in one area, but decreasing it by the same amount in another, cancels out. The objective of the order curtailment sharing is to pro-rate the available supply across the price taking orders in the areas that will be affected by the order curtailment situation. Of course exchanging the order curtailments can only be done to the extent network constraints allow this.

Differences ATC and FB

Although precisely the same order curtailment sharing approach is used under FB and ATC there will be some practical differences. We assume the first welfare maximisation step will results in a partially congested CWE region. Under ATC two neighbouring countries could both end up in a order curtailment situation: they would fully import from their other neighbours, but between the two try to share the order curtailment to the extent capacity between them allows this. Under FB the partial congestion implies that at least one CB will be active. Depending on the respective flow factors of the two markets in order curtailment, this would allocate the imports differently. So much so, that possibly one market can import its entire price taking demand, and more, resulting in the order curtailment situation being lifted. At the same time the other market could see its order curtailment aggravated. Since this welfare maximising solution only has 1 market in order curtailment, the order curtailment sharing phase will be omitted.

7.2. Simplified welfare model

This section describes the simplified welfare model used to find some of the quantitative results of section 3.

Sets

Set	Description	Index
Z	Set of all zones	z
CB	Set of all critical branches (and critical outages)	cb

Parameters

Parameter	Description
$PTDF^{cb}_{z}$	**P**ower **T**ransfer **D**istribution **F**actor for the influence of zone z on CB cb
RAM_{cb}	**R**emaining **A**vailable **M**argin for CB cb

Variables

Variable	Description	Range	Primal/Dual
nex_z	Net position in area z	$\mathbb{R}$	Primal
$flow_{i,j}$	flow between areas i and j	≥ 0	Primal
μ_{cb}	Shadow price of CB $cb \in CB$	≥ 0	Dual
π_{sys}	System price	$\mathbb{R}$	Dual
$\pi_z^{Intuitive}$	Offset on market price z to make it intuitive	$\mathbb{R}$	Dual
λ_{ij}	Shadow price of forbidden (non-intuitive) flows	≥ 0	Dual

Model

Primal formulation

Objective function – maximize congestion rent

$$\max - \sum_{z \in Z} \left(nex_z \cdot P_z \right)$$

s.t.

Constraint	Index	Shadow price	ID: Name
$\sum_{z \in Z} \left(nex_z \right) = 0$		$\left(\pi_{sys} \right)$	(1) Balance
$\sum_{z \in Z} PTDF_z^{cb} \cdot nex_z \leq RAM_{cb}$	$\forall cb \in CB^{FB}$	$\left(\mu_{cb} \right)$	(2) PTDF
$\sum_{j \in Z} \left(flow_{zj} \right) - \sum_{i \in Z} \left(flow_{iz} \right) - nex_z = 0$	$\forall z \in Z$	$\left(\pi_z^{\mathrm{int}uitive} \right)$	(3) Flow decomposition
$flow_{ij} \leq 0$	$\forall (i, j) \in Z \times Z \mid P_i > P_j$	$\left(\lambda_{ij} \right)$	(4) Intuitive flows

Note that the objective function to maximise welfare in the context of this model is equivalent to maximising congestion rent. We defined welfare:

Welfare = consumer surplus + producer surplus + congestion rent

However if in our model we a-priori fix the prices of the markets, this is equivalent to having one large marginal order in each market, none of which generate any surplus. I.e. the only non-zero welfare component remains the congestion rent.

Constraint (3) finds a decomposition of net positions into flows. This constraint is only used to find intuitive results. Any non-intuitive flows are forbidden by constraint (4). The constraints in (4) are only imposed for the FBI simulations, but are deactivated in the FB simulations.

The rest of the constraints are self-explanatory.

Dual formulation

$$\min \sum_{z \in Z} \left(RAM_{cb} \cdot \mu_{cb} \right)$$

s.t.

Constraint	Index	Shadow price	ID: Name

$\pi_{sys} + \sum_{cb} PTDF_z^{cb} \cdot \mu_{cb} - \pi_z^{intuitive} = -P_z$	$\forall z \in Z$	(nex_z)	(5) Price relation
$\pi_i^{intuitive} - \pi_j^{intuitive} + \lambda_{ij} \geq 0$	$\forall (i,j) \in Z \times Z$	$(flow_{ij})$	(6) Intuitive price difference

From the dual formulation it becomes immediately apparent that the model is unbounded in the absence of FB constraints: unlike the normal formulation (cf. intuitive FB description http://www.casc.eu/media/Annex%2016_18%20Flow-Based%20intuitive%20explained.pdf) there are no variables related to orders, and only the FB domain imposes constraints.

Limitations of the model

An important assumption the model makes is the one of perfect elasticity: the prices of the different markets are fixed a-priori by effectively adding infinite buy and sell into the market at the set price. When considering welfare maximisation in a normal market coupling setting, the elasticity of the market means that each additional MWh that is being exchanged will bring prices closer together. This also means there is an optimal solution, where all market share the same price: further exchanges will diverge prices, and decrease welfare.

Figure 14 illustrates the welfare function by colour: the colder (more blue) the colour, the lower the welfare, the warmer (more red) the colour, the higher the welfare. The two dimensions correspond to the net positions of two markets. The dark red spot in the middle of the left hand figure corresponds to the point where all prices have converged. The purplish FB domain is sketched in the top right. An optimal solution is sketched by the yellow dot. The purple arrow is perpendicular to the iso-welfare curve corresponding to the optimal solution. Therefore it points in the direction that will increase welfare most. Note that the direction of this arrow differs, depending where you are on the iso welfare curve;

The right hand side of Figure 14 illustrates a similar situation, but now the welfare does not correspond to an actual order book, but rather to our perfectly elastic markets. Because the prices of the markets never change, it will always be possible to generate more welfare by exchanging more energy. I.e. the direction of the arrow pointing towards the steepest welfare ascend does not change depending where you are on the iso welfare curve, but always points in the same direction. As a consequence unlike in a realistic FB situation where solutions are often found on planes of the FB domain, in our model we always end up in vertices of the FB domain.

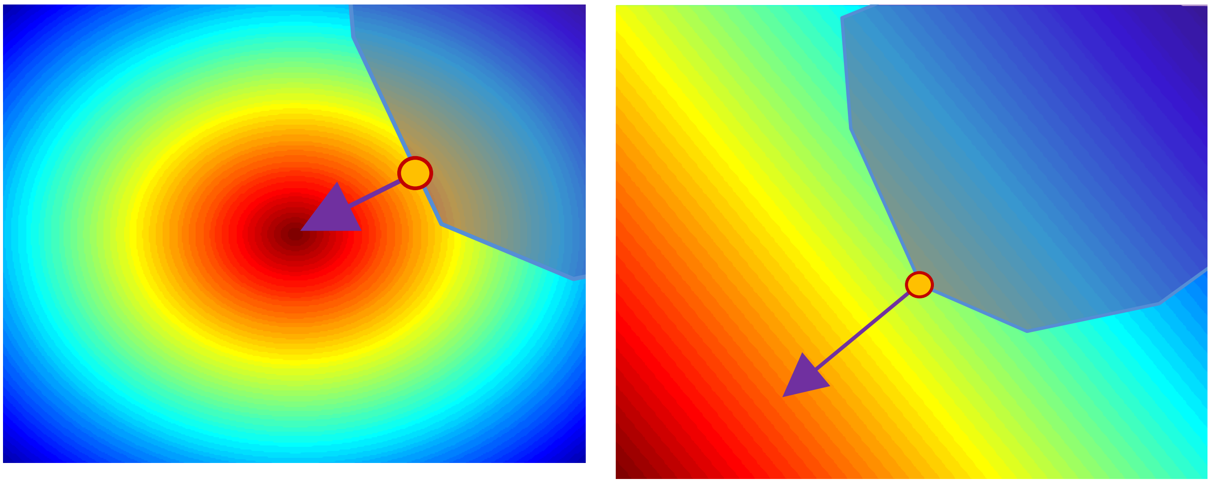

Figure 12 Illustration of a welfare function and a FB domain. LHS: normal order books, RHS: perfectly elastic markets; The yellow dots correspond to the optimal solutions, inside the FB domain;

This effect can also be observed when testing the model. The model fixes prices of the four CWE areas, and looks for the net positions that optimize welfare (or CR, since these are equivalent when fixing prices). We can test the model by looking back at the parallel run results: we feed our model the prices of the parallel run, and check whether it successfully replicates the net positions.

In Figure 16 the results for the BE positions following this process are illustrated. The idea would be that the net positions are identical, but clearly they are not. If we focus on the congestion rents in Figure 17, we notice between our model and the parallel run these are (practically) identical. Therefore we conclude the model does work. In fact what happens is all illustrated in Figure 14: the parallel run finds result on planes of the FB domain, but our model finds solutions on vertices. In terms of welfare our model manages to find solutions that are marginally better, because our prices are elastic, whereas in the parallel run they were not. The differences in welfare are so small, they cannot even be observed in Figure 17.

Finally we consider the non-zero shadow prices of both our model and the parallel run in Table 1. Here again we notice the effect that our model finds vertices, even when the parallel run result corresponded to a solution on a plane: some CBs that were not active (had zero shadow price) became active, although with very small shadow price in our model.

We consider hour 17 in slightly more detail. For this hour an NL import constraint was active, so the problem reduces to a more manageable 3 market example. We consider the FB domain using different 2D projections in Figure 15. For the parallel run result the DE export constraint in that hour was not active, however in the model this constraint becomes active too, ever so slightly increasing the congestion rent. The consequence is that BE under the model can import less.

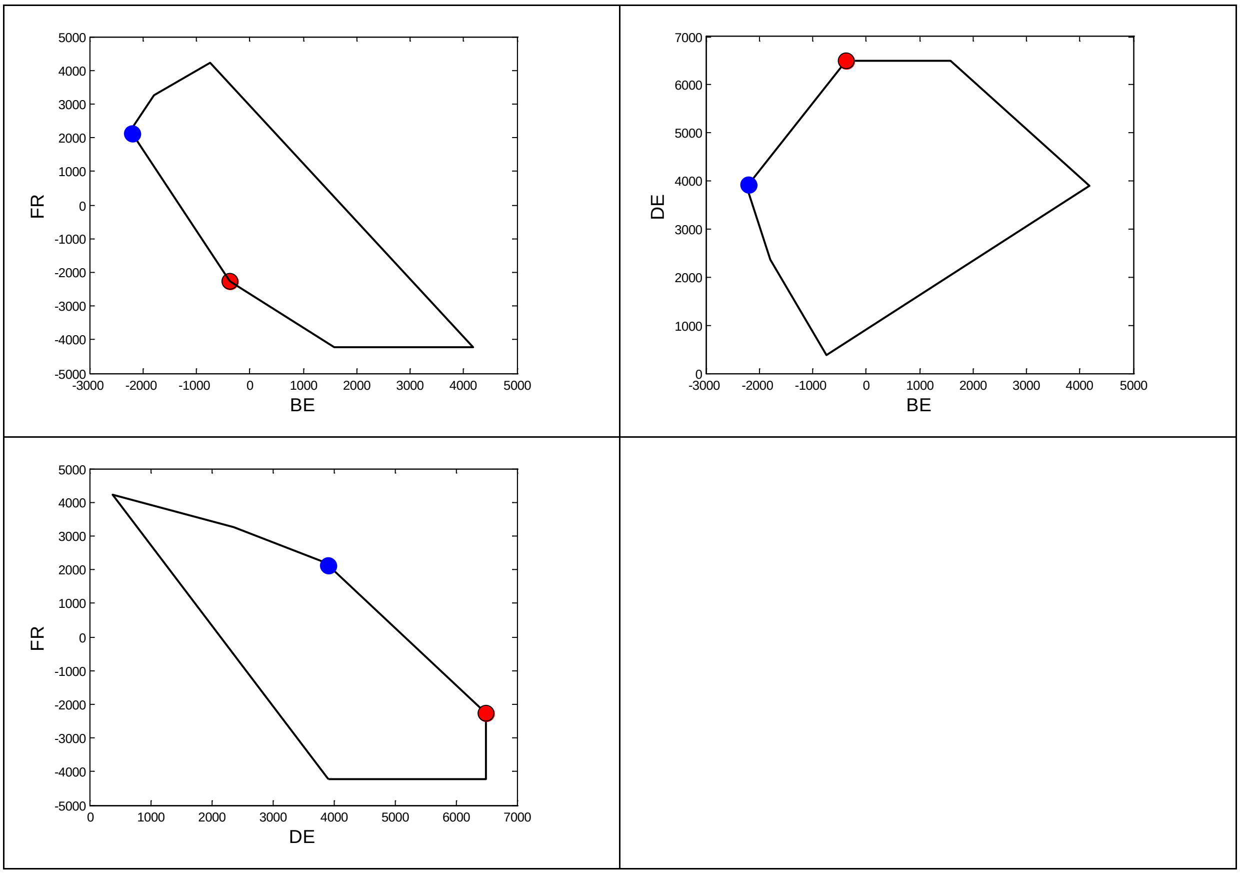

Figure 13 projection of FB domain for 30 August 2014, hour 17. Parallel run solution in blue, model solution in red.

Also recall that the CWE FB model has four net positions to optimise and one balance constraint that needs to be respected. This leaves three degrees of freedom, so at most 3 CBs can be active (in case of degeneracy even more than 4 CBs can be active). For hour 21 and 22 we see that both our model and the parallel run result had three active CBs with nearly identical shadow prices. If we come back to Figure 16 and look again at the BE positions, we note that precisely for these two hours there was no difference between the model and the parallel run results.

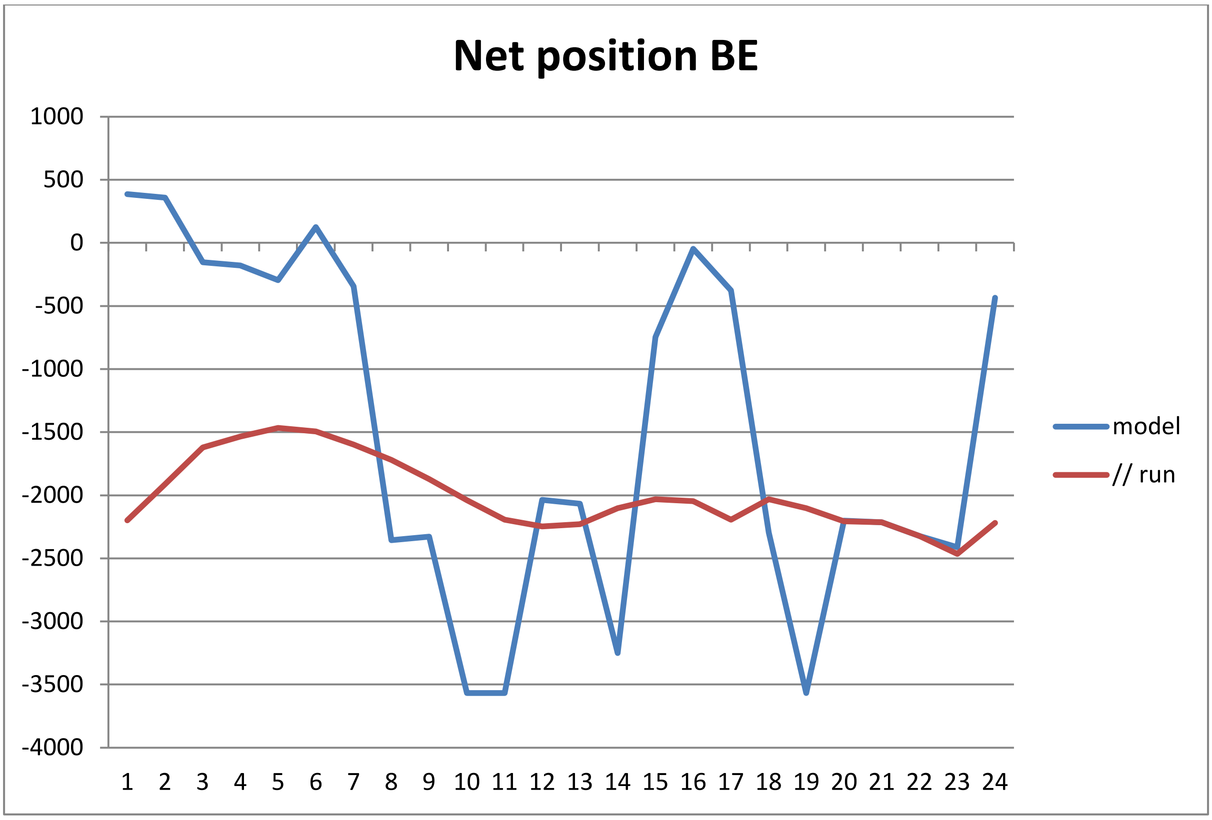

Figure 14 BE net positions for 30 August 2014, resulting from our model, when feeding the parallel run prices in blue. In red the corresponding parallel run results.

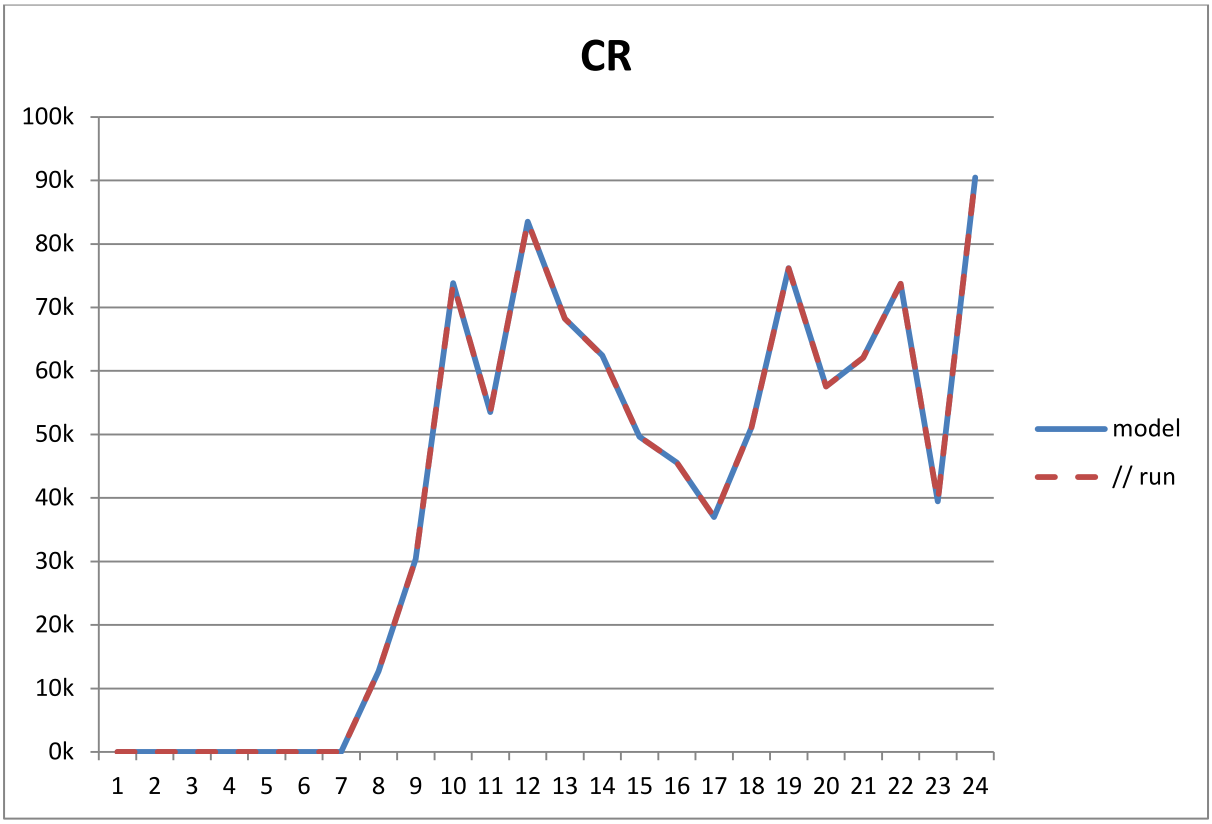

Figure 15 Congestion rent for 30 August 2014, resulting from our model (blue) and the parallel run (red).

Hour	ROW	BE	DE	FR	NL	RAM	model	parallel run
8	384	-0.09642	0.09178	0.16903	0.0342	871	0.01557	0.00000
8	1719	0	0	0	-1	3841	0.00120	0.00000
8	2599	0.06726	0.1875	0.31714	0.09654	979	12.94969	12.95122
9	206	0.06727	0.1875	0.31786	0.094	1009	30.05794	30.11669
9	641	0.0298	0.27667	0.17574	0.01494	1279	0.02470	0.00000
9	2384	-0.09641	0.09178	0.1694	0.03331	883	0.05333	0.00000
10	33	0.02985	0.27732	0.17646	0.01483	1221	0.02543	0.00000
10	1434	-1	0	0	0	3567	0.01261	0.00000
10	1633	-0.09638	0.09227	0.1685	0.03349	810	91.07392	91.13570
11	148	-0.09638	0.09228	0.16835	0.0334	827	43.94075	43.93798
11	1004	0.02985	0.27731	0.17667	0.01433	1249	13.73781	13.74496
11	1233	-1	0	0	0	3567	0.00058	0.00000
12	480	-0.09638	0.09228	0.16834	0.03326	820	59.23700	59.20743
12	1151	0.02985	0.27731	0.1767	0.01397	1239	28.18374	28.21139
12	2420	0	0	0	-1	3841	0.00193	0.00000
13	1024	0	0	0	-1	3841	0.00372	0.00000
13	1660	-0.09638	0.09228	0.16872	0.03349	841	0.01806	0.00000
13	2744	0.02985	0.27731	0.17645	0.01483	1222	55.83364	55.85034
14	219	0.02985	0.27731	0.17654	0.01501	1224	50.98207	50.98707
14	1280	0	1	0	0	6496	0.00024	0.00000
14	2072	0.16679	0.40843	0.2599	0.59194	1077	0.01546	0.00000
15	310	0.00886	0.06971	0.03312	-0.11303	728	0.04008	0.00000
15	1075	0	1	0	0	6496	0.00174	0.00000
15	1700	0.02985	0.27731	0.17582	0.01465	1289	38.49440	38.53390
16	372	0.02985	0.27731	0.17506	0.01786	1275	35.67247	35.71503
16	2175	0	1	0	0	6496	0.01249	0.00000
16	2504	0	0	0	-1	3841	0.00229	0.00000
17	275	0	1	0	0	6496	0.00948	0.00000
17	389	0.02985	0.27732	0.17503	0.0173	1325	15.84240	15.87528
17	2763	0	0	0	-1	3841	4.15118	4.15077
18	997	-0.09644	0.09202	0.16852	0.0341	807	63.28527	63.31004
18	1093	0	0	0	-1	3841	0.00111	0.00000
18	1752	0.02977	0.27585	0.17592	0.01887	1353	0.01324	0.00000
19	1202	-1	0	0	0	3567	0.00966	0.00000
19	2098	0	-1	0	0	4904	0.00420	0.00000
19	2719	-0.09644	0.09202	0.16953	0.03437	771	98.77183	98.79909
20	249	0	0	0	-1	3841	0.00240	0.00000
20	1737	-0.09644	0.09203	0.16899	0.0341	800	71.87505	71.88306
20	2522	0.02977	0.27585	0.17613	0.01887	1318	0.01508	0.00000
21	1238	-0.09644	0.09203	0.16892	0.03367	807	46.54717	46.55299
21	1366	0.02977	0.27585	0.17618	0.01699	1324	16.24372	16.24253
21	1933	0	0	0	-1	3841	0.78866	0.78943
22	1015	-0.09644	0.09203	0.1689	0.03415	839	10.98391	10.97192
22	2048	0	0	0	-1	3841	5.35456	5.35288

22	2775	0.02977	0.27585	0.1762	0.01922	1325	33.15939	33.16975
23	954	-0.09644	0.09203	0.16805	0.03409	886	0.00410	0.00000
23	1521	0	0	0	-1	3841	0.00116	0.00000
23	1993	0.02977	0.27585	0.17647	0.01886	1307	30.19029	30.19288
24	20	0	1	0	0	6496	0.00414	0.00000
24	1284	0.0091	0.07493	0.03452	-0.11834	790	0.05214	0.00000
24	2377	0.02977	0.27836	0.17619	0.01972	1256	71.97565	72.00898

Table 1 PTDFs and shadow prices for CBs that were active under our model for 30 August 2014