Energy 34 (2009) 228–234

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Market coupling and the importance of price coordination between power exchanges

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ARTICLE INFO

Article history:
Received 3 July 2007
Available online 13 June 2008

Keywords:
Pricing
Electric market equilibrium
Operational research
Power system economics
Duality

ABSTRACT

In Europe, market coupling stands for a further integration of wholesale trading arrangements across country borders. More specifically, it refers to the implicit auctioning of cross-border physical transmission rights via the hourly auctions for electric energy organized by power exchanges (PEXs) one day ahead of delivery. It therefore implies that the PEXs can optimize the clearing of their day-ahead auctions. Due to verticals in the aggregated order curves, the optimal solution can be settled at different prices. In order for prices to give correct locational signals for network development, generation and consumption, price coordination between exchanges is necessary. The paper illustrates this issue, its relevance and discusses how to deal with it.

1. Introduction

In Europe, generators self-schedule and they do this by submitting a production program to the network operator. Which and when generators are turned on and run is the result of trading in several types of markets. Trading is mainly bilateral, but in most countries this is supplemented with auction trading organized by power exchanges (PEXs) one day ahead of delivery for every hour of the next day. The auctions are used by market parties to fine tune their portfolios, which for instance means that generators can be on the supply as well as demand side depending on whether they are long or short. The PEXs use simple rules to settle contracts one day ahead of delivery when it is not worth getting into time consuming bilateral negotiations. Additionally, the exchanges act as counter-party for all transactions. The traded volume on the PEXs is typically 10% of consumption.

While wholesale trading within countries is not constrained by the network, it is constrained at the borders where there are structural bottlenecks. The transmission system operators (TSOs) determine transfer capacities (so-called net transfer capacities) independently per border and before trading actually takes place. In other words, before it is known how flows will be distributed over the different interconnections and without taking the interdependencies of a meshed network into account. About 10% of consumption is currently traded across borders in Europe.

As discussed in [1], the European version of a flow gate approach is not the most efficient way of dealing with the scarce network resources. This is not about to change soon, but what is changing is how these capacities are allocated to market parties. Non-market-based allocation methods have largely been abolished and replaced by separate auctions per border. The auctions are organized by the TSOs and are typically for yearly, monthly and daily physical transmission rights.

Arbitrage between the various PEXs is therefore already possible but explicit, requiring the purchase of physical transmission rights on a contract path. Besides being constrained by the available border capacities, arbitrage is also constrained by the time lag between the closing of the different border and PEX auctions and the uncertainty that this brings, especially given the high price volatility. Several empirical studies that compare the prices of border capacity with the price difference between exchanges indeed indicate that arbitrage is currently inefficient (see for instance [2]).

Market coupling refers to the implicit auctioning of physical transmission rights via the hourly auctions organized by PEXs one day ahead of delivery. Nord Pool (Elspot) already does this for several years for the total available capacity on the internal borders of the Scandinavian countries. Since November 2006, the capacity available day-ahead on the internal borders of France, Belgium and the Netherlands that used to be auctioned in a separate market organized by the respective TSOs is now used by the exchanges to optimize the clearing of their day-ahead auctions. This so-called trilateral market coupling (TLC) initiative is expected to be extended to include more countries.

Market coupling implies that exchanges can optimize the clearing of the offers and bids for electric energy submitted to

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doi:10.1016/j.energy.2008.04.013

their day-ahead auctions. As such, total gains from trading are increased. Often quoted benefits are also reduced price volatility and increased liquidity as orders can be matched across borders. Due to verticals in the aggregated order curves, the optimal solution can, however, be settled at different prices. In order for prices to give correct locational signals for network development, generation and consumption, price coordination between exchanges is necessary.

Section 2 introduces the market coupling optimization problem. Section 3 introduces the widely accepted approach to settle trading with network constraints, i.e. locational marginal pricing (LMP). Section 4 then illustrates that locational marginal prices (LMPs) have important properties and that they are not always uniquely determined. Section 5 discusses price coordination between exchanges, including its relevance and how it is being dealt with in the TLC initiative.

2. Market coupling optimization problem

The market coupling optimization problem involves demand and supply orders of different exchanges that need to be matched in order to maximize the total gains from trading. This means that the cheapest supply orders are matched with the most willing to pay demand orders. The only complexity in comparison with a single exchange optimization problem is that these orders come from different exchanges which represent a different network location. The demand and supply volumes traded on the different exchanges do not have to be equal, as long as the traded volumes equalize in total and the resulting flows between locations are feasible given the limited available network capacity.

For the market coupling optimization problem, the topology and capacities of the simplified network that need to be taken into account are given as they are pre-determined by the involved TSOs. Given is also the volumes and prices of the orders that have been submitted. What needs to be determined is which orders are accepted at which hourly price for every exchange. The optimization problem can therefore be formulated as follows:

Maximize the value of demand minus the cost of supply:

$$\underset{q}{\text{Max}}\left(\sum_{z}\left(\sum_{j} q_{jz}P_{jz} - \sum_{i} q_{iz}P_{iz}\right)\right) \quad (1)$$

with P_{jz} is the price limit of demand side order j submitted to exchange z (or introduced at location z), P_{iz} is the price limit of supply side order i submitted to exchange z (or introduced at location z), q_{iz}, q_{jz} is the decision variable representing the accepted volume of the respective orders

Subject to the order constraints (2) and (3), making sure that the accepted volume is not higher than the volume limit of an order:

$$q_{iz} \leqslant Q_{iz} \quad (2)$$

$$q_{jz} \leqslant Q_{jz} \quad (3)$$

With Q_{jz} is the volume limit of demand side order j submitted to exchange z (or introduced at location z), Q_{iz} is the volume limit of supply side order i submitted to exchange z (or introduced at location z).

And subject to DC load flow network constraints (4) and (5), which are a simplification of the actual power flow equations as for instance discussed in [3]. Constraints (4) equalize the net injections with the off-takes at every location. Constraints (5) make sure that the flow is not higher than the available capacity between the locations:

$$\forall z : \sum_{i} q_{iz} - \sum_{x} q_{jz} - \sum_{x} B_{zx}(\theta_z - \theta_x) = 0 \quad (4)$$

$$\forall z, x \in Z : B_{zx}(\theta_z - \theta_x) \leqslant Cap_{zx} \quad (5)$$

with B_{zx} is the susceptance of the interconnector between zone z and x, θ_z is the voltage angle, Cap_{zx} is the capacity of the interconnector between z and x.

Note that in practice, the exchanges solve this optimization problem for every hour of the next day and the hours are interdependent because of so-called block orders [4]. For reasons of clarity, abstraction is made of block order in this paper.

3. Price properties

Locational marginal prices (LMPs) are the most obvious choice to settle the optimal solution to the market coupling optimization problem. It basically means that the orders of an exchange are settled at the price that corresponds to the shadow price of its market clearing constraint (4). LMPs have interesting properties. They for instance give efficient locational signals for network development, generation and consumption. LMP is also widely used; especially in the North American markets (see for instance [5]). Although a lot of literature is available discussing the properties of LMPs (see for instance [6]), much less is available on implementation issues of LMP. This paper discusses an implementation issue related to the verticals in the aggregated order curves of the exchanges that is relevant for the European context.

The properties of LMPs can be derived from the optimality conditions of the market coupling optimization problem (1)–(5) as has been done in [7] for the more generalized problem. This leads to the following equations that define the necessary relation between the LMPs and the shadow prices of (5), which correspond to the value of the interconnections:

$$\forall z, x : \sum_{x} B_{zx}[p_z - p_x + \mu_{zx} - \mu_{xz}] = 0 \quad (6)$$

with p_z is the LMP, or simply price corresponding to location z. Note that demand and supply orders of a single location or exchange are cleared at the same price. μ_{xz} is the value of the interconnector between x and z, in the direction x–z, which corresponds to the shadow price of (5). Therefore, this price is zero if constraint (5) is non-binding, which is the case when the interconnector is not fully used.

Note that LMPs are not always as intuitive as one might think. Based on simplified examples in non-meshed networks, these prices have sometimes been attributed properties that the approach cannot deliver. For a discussion of common misunderstandings, see for instance [7,8].

4. Freedom in prices

4.1. Price ranges

Consider three exchanges PX1, PX2 and PX3 to which the orders listed in Table 1 are submitted. Fig. 1 illustrates the implied aggregated order curves for the three exchanges separately and jointly. If the exchanges are not coupled they would have cleared a volume of, respectively, 100, 100 and 100 MW h at a price of 10, 25 and 90€/MW h. Total gains from trading in that case would have been 18,500€ ((PX1:) 100 MW h (90–10€/MW h)+(PX2:) 100 MW h (90–25€/MW h)+(PX3:) 100 MW h (90–50€/MW h)). If the exchanges would be coupled without binding network constraints,

Table 1
Demand and supply orders introduced to PX 1 to 3

PX1	PX2	PX3
Demand orders (bids)		
100 MW h@ 90€/MW h	100 MW h@ 90€/MW h	200 MW h@ 90€/MW h
Supply orders (offers)		
300 MW h@ 10€/MW h	175 MW h@ 25€/MW h	100 MW h@ 50€/MW h

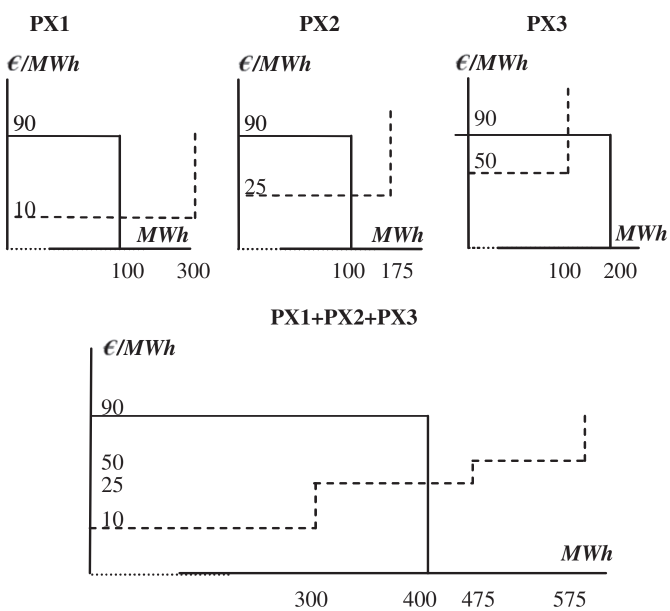

Fig. 1. Aggregated order curves of three PEXs separately and jointly.

they would have cleared a total volume of 400 MW h at a price of 25€/MW h. In comparison with the non-coupled situation, the volume traded in total has increased with 100 MW h and total gains from trading have gone up to 30,500€ (300 MW h (90–10€/MW h)+100 MW h (90–25€/MW h)). The difference, 12,000€, is because at PX3 more demand can be supplied (100 MW h (90–10€/MW h)) and additionally the more expensive supply offer at PX3 can be replaced with the cheaper supply offer introduced at PX1 (100 MW h (50–10€/MW h)).

The optimal solution implies a transfer of 200 MW h from PX1 to PX3, i.e. an injection in the network of 200 MW h at location 1 and a withdrawal of 200 MW h at location 2. Fig. 2 illustrates the possible locational prices and their corresponding export level. Note that these prices reflect the property of LMP that there is a single price per location to settle demand and supply at that location. Take for instance PX1:

- No supplier is offering at a price below 10€/MW h, while at such low prices demand will definitely want to be supplied fully, so that the corresponding import level for prices lower than 10€/MW h is 100 MW h.
- Demand does not want to pay more than 90€/MW h, while at such high prices supply will definitely want to be supplied fully, so that the corresponding export level for prices higher than 90€/MW h is 300 MW h.
- In between 10 and 90€/MW h demand wants to be fully supplied and suppliers want to supply all they offered as they can make a profit, so that the corresponding export level for prices between 10 and 90€/MW h is 200 MW h.
- If the price is 10€/MW h/90€/MW h supply/demand can be curtailed as the orders are marginally accepted at those prices, so that there are several corresponding import/export levels, as illustrated in Fig. 2.

In other words, an export of 200 MW h corresponds to several possible locational prices at PX1. As illustrated in Fig. 2, the same counts for PX3, which we will refer to as locational price ranges. Therefore, the LMP property of having a single price per location alone does not fix the prices in this illustration. Another LMP property is that if there are no binding network constraints, the network does not generate revenue. Fig. 3 illustrates the impact on the network of the transfer between PX1 and PX3. Note that it is assumed that all interconnector susceptances are equal so that 1/3 of the transfer goes via PX2 and 2/3 goes via the direct interconnection. Assuming that there is enough capacity to make this solution feasible, the remaining optimality conditions (6) translate into:

$$2p_1 - p_2 - p_3 = 0 \tag{7}$$

$$-p_1 + 2p_2 - p_3 = 0 \tag{8}$$

$$-p_1 - p_2 + 2p_3 = 0 \tag{9}$$

These equations basically imply that the locational prices have to be equal. Given that the price of PX2 is fixed at 25€/MW h (Fig. 2: there is no locational price range for PX2), this is the price for the three exchanges. In conclusion, an important LMP property is that LMPs are equal if there is no congestion in the network. Furthermore, in this example, there is only one set of prices that satisfies all LMP properties.

4.2. Alternative sets of LMPs

If we introduce binding network constraint to the example introduced in the previous section, the optimal solution changes. Fig. 4 illustrates this with a binding capacity constraint between PX1 and PX3. In this network, a transfer between PX2 and PX3 is more interesting than a transfer between PX1 and PX3, because the latter uses more of the scarce network resource (double the amount) which offsets the supply cost advantage PX1 (10€/MW h) has over PX2 (25€/MW h). In this network setting, the optimal solution is to transfer as much as possible between PX2 and PX3 and to use what remains on the interconnector between PX1 and PX3 for a transfer between these exchanges, as illustrated in Fig. 4.

Fig. 5 illustrates that the optimal solution yields two price ranges (PX2: $25<p<90$; PX3: $50<p<90$), but the export level of PX1 implies a price of 10. Given that there is a binding constraint between PX1 and PX3 so that μ_{13} is positive and given that p_1 is 10, (6) translates into:

$$20 - p_2 - p_3 + \mu_{13} = 0 \tag{10}$$

$$-10 + 2p_2 - p_3 = 0 \tag{11}$$

$$-10 - p_2 + 2p_3 - \mu_{13} = 0 \tag{12}$$

Eqs. (10)–(12) is a set of 2 two linear independent equations with three unknowns, meaning that there is some freedom in the prices. Indeed, solving the example in Matlab using the linprog solver yields prices of 10, 41 and 73€/MW h, respectively, for PX1, PX2 and PX3 and solving it with the CPLEX solver yields prices of 10, 30 and 50€/MW h (Table 2). In other words, the example clearly illustrates that prices can differ significantly depending on which software is used to solve the problem. If no additional

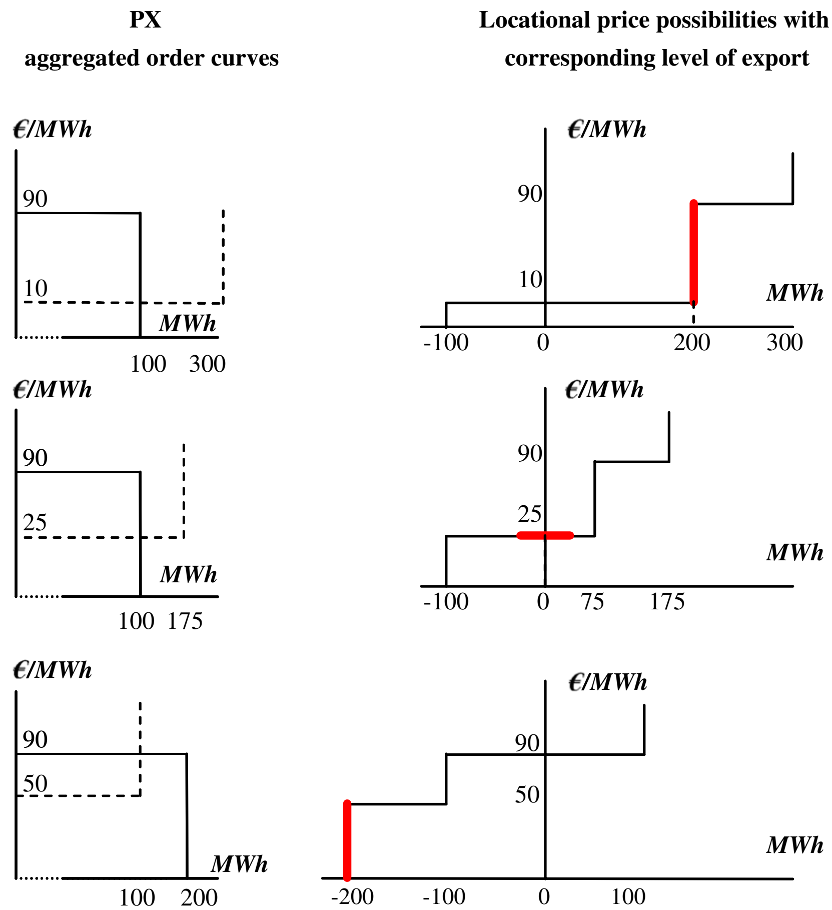

Fig. 2. Locational price ranges corresponding to the optimal solution reported in Fig. 1 as the intersection of aggregated order curves joined for the three exchanges.

method is applied to consciously choose between the alternative sets of LMPs, the solution will depend on the solver software that is used.

5. Price coordination

5.1. Importance of price coordination

Perhaps the simplest way of dealing with price ranges is to allow every exchange to independently choose which price they take of the possible prices that correspond with the optimal export level that comes out of the market coupling problem. The consequence would, however, be that even the most basic LMP property, which is that prices should be equal if there is no congestion, is not necessarily satisfied. Even though the most willing to pay demand would still be matched with the cheapest suppliers, the distribution of gains from trading would be different. In this case, the network could generate congestion rents, giving incentives to further invest in the network, while increasing the network capacity would not improve welfare. In other words, only LMPs give correct locational signals for network development, generation or consumption. Therefore, the best way to coordinate prices is to use the shadow prices of the market clearing constraint, which are the LMPs.

The remaining question is what to do in case there are alternative sets of LMPs. Consider the illustration from the previous section. Table 2 summarizes some of the possibilities to choose from. As indicated in the table, the value of the interconnector between PX1 and PX3 (μ_{13}) is always positive. This is because the interconnector between PX1 and PX3 is congested. The value of a congested interconnector (€/MW h) is equal to the congestion rents (€) divided by the flow over the interconnector (MW h). Congestion rents are the result of transfers between exchanges with different prices. In the illustration, prices in PX1 and PX2 are lower than in PX3 so that transferring energy from PX1 and PX2 to PX3 generates a revenue that is called congestion rent. In general, congestion rents can be expressed in function of the value of the interconnectors μ_{zx}:$z, x \in Z$, but also as a function of the LMPs p_z:$z \in Z$, which is equivalent:

$$\sum_z \sum_x B_{zx}(\theta_z - \theta_x) \cdot \mu_{zx} = \sum_z (\sum_j q_{jz}* - \sum_i q_{iz}*) \cdot p_z \tag{13}$$

With $q_{iz}*$, $q_{jz}*$ is the optimal traded volumes, resulting from the solving the market coupling problem (1)–(5).

Note from Table 2 that the signal to invest in the network (μ_{13}) can be double as high in the illustration, depending on whether congestion rents are minimized or maximized when choosing between different sets of LMPs. The highest μ_{13} value is actually the negative effect on total gains from trading if the capacity would be reduced with 1 MW, while the lowest μ_{13} value is the positive effect on total gains from trading if the capacity would be increased with 1 MW:

- 1 MW more, is 3/2 MW h more transfer between PX1 and PX3, which would mean replacing 3/2 MW h of supply in PX3 at 50€/MW h with supply from PX1 at 10€/MW h, which is a gain of 60€ (3/2(50–10)).

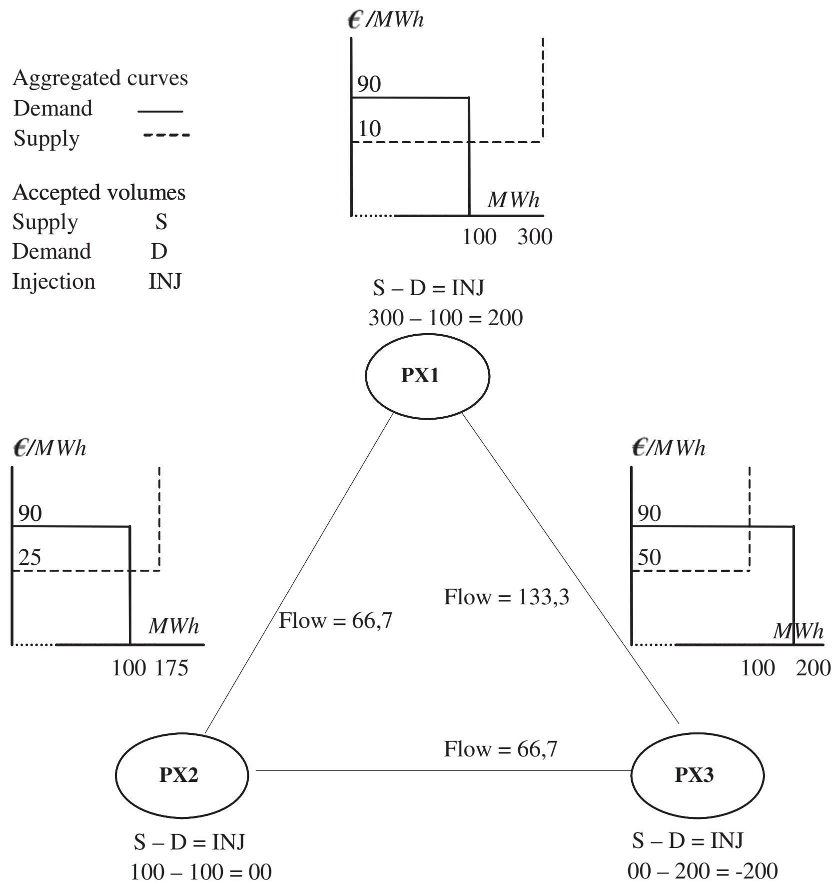

Fig. 3. Impact optimal solution (Fig. 1, intersection of aggregated order curves joined for the three exchanges) on the network.

- 1 MW less, is 3/2 MW h less transfer between PX1 and PX3, which would reduce by 3/2 MW h demand in PX3 with a value 90€/MW h and supply in PX1 at 10€/MW h which is a loss of 120€ (3/2(90–10)).

In principle, the highest and the lowest value are as relevant, but in a European context with scare interconnection capacity between countries, the question is rather which interconnector to further expand than which to maintain. This is one argument in favor of minimizing the congestion rents when choosing between sets of LMPs. Another argument is that one of the main concerns at the moment in Europe is that only a small fraction of the congestion rents is used to invest in the network.

It can therefore be concluded that a good and straightforward way to choose between alternative sets of LMPs is to minimize congestion rents.

5.2. Minimizing congestion rents

A general approach to determine LMPs would therefore be to first solve the market coupling problem (1)–(5). Once the optimal traded volumes ($q_{iz}*$, $q_{jz}*$) are known, also the price ranges are known for every exchange. The optimization problem can therefore be formulated as follows:

Minimize congestion rents:

$$\sum_z \left(\sum_j q^*_{jz} - \sum_i q^*_{iz} \right) \cdot p_z \qquad (14)$$

with p_z is the decision variable, representing the price corresponding to location z.

Subject to the price ranges and (6), which are the optimality conditions of the market coupling problem. If applied to the illustration from the previous section, solving this simple linear programming (LP) problem yields prices of 10, 30 and 50€/MW h for PX1, PX2 and PX3 (Table 2). Eqs. (10) or (12) than imply that the value of the interconnection between PX1 and PX3 is 60€/MW h, which is the value that corresponds to 1 MW capacity increase of that interconnection as discussed in the previous subsection. Note that if the market coupling problem has to deal with more constrained interconnectors as in the illustration, this only means that the above LP problem will contain more variables.

5.3. Relevance of price coordination

Which price is chosen on a price range is of course only relevant if coupled exchanges are often faced with such price ranges and if they are significant. Fig. 6 illustrates the price ranges on Belpex for the first 2 months of operation. In 30% of the hours observed there is no price range, and in 80% of the hours the price range is smaller than 20€/MW h. This implies that in 20% of the hours the price is larger than 20€/MW h. Note that there are even a few observations with price ranges peaking close to 400€/MW h, even though the figure stops at 160€/MW h. Given that a typical wholesale price is 50€/MW h, this is a very relevant part of the price formation on the PEXs.

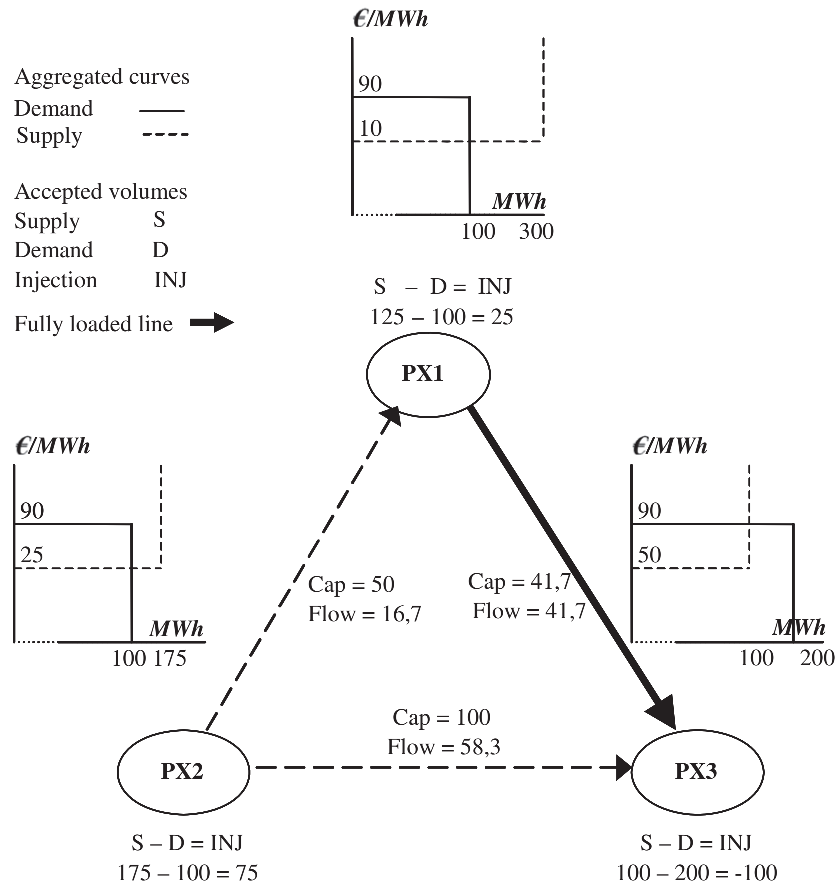

Fig. 4. Introducing price sets.

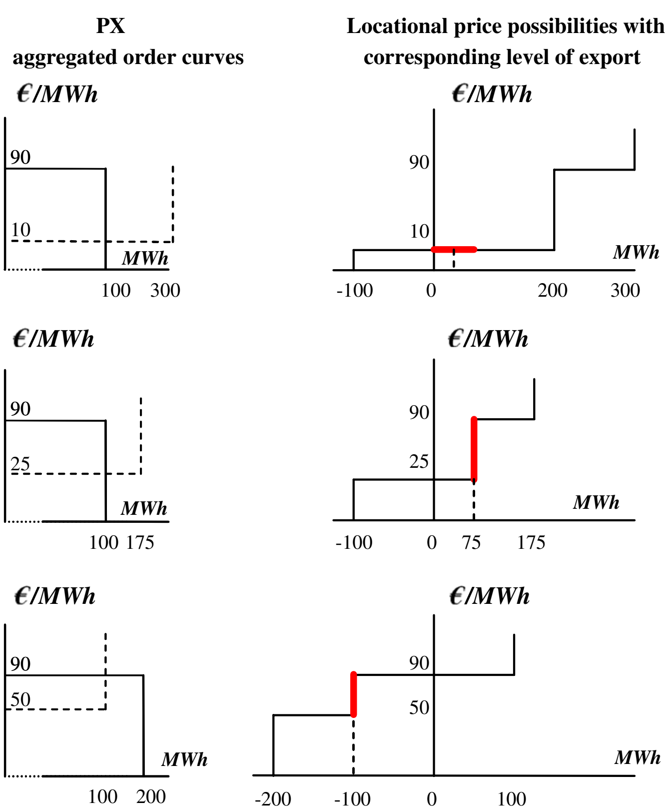

Fig. 5. Locational price ranges for solution in Fig. 4.

Table 2
Demand and supply orders introduced to PX 1 to 3

(€/MW h)	Linprog	CPLEX	Min CR	Max CR
PX1	10	10	10	10
PX2	41	30	30	50
PX3	73	50	50	90
μ_{13}	94	60	60	120

For the moment, the TLC initiative encompasses only France, Belgium and the Netherlands, which are aligned in that order. As the internal borders are not meshed, LMPs have more straightforward properties. For instance, the price of an interconnector is the difference between the location prices a both sides of the interconnector. Additionally the flow always goes from a high price region to the low price region, which is not necessarily the case if the network is meshed.

In [9], the price determination in case of price ranges is explained for TLC. The approach is specifically for three aligned markets. It is based on taking the middle price of an overlap between price ranges, subject to the LMP properties, which are called high level properties of the algorithm. If market coupling is extended to more markets and meshed networks, the approach discussed in this paper could be used, which is to minimize congestion rents, subject to the optimality conditions of the market coupling problem.

6. Conclusions

Market coupling means that exchanges optimize the clearing of the electric energy orders submitted to their day-ahead auctions. In

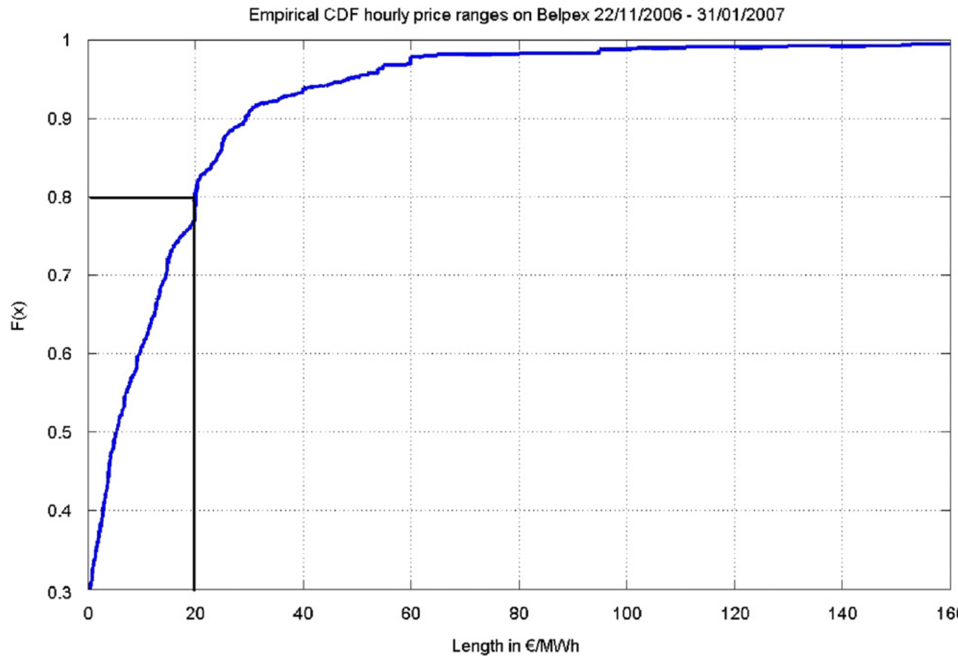

Fig. 6. Observations from Belpex.

doing so, orders introduced at different locations are exchanged to the extent that the available network capacities allow. Prices at these optimal exchange levels can be undetermined on an interval or price range due to the verticals in the aggregated order curves. For a single PEX, a simple rule such as taking the middle price of the possible prices is sufficient. For coupled exchanges, coordination is, however, necessary in order not to distort the locational incentives for network development, generation and consumption. Additionally, it has been discussed that LMPs can be derived from the optimality conditions of the market coupling optimization problem, but that these conditions do not necessarily uniquely determine the prices, in which case it has been discussed that the set of prices needs to be chosen that minimizes congestion revenues.

Acknowledgments

The authors thank the three anonymous referees and the editor for their valuable comments. The analysis and conclusions are of course the sole responsibility of the authors.

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