Inefficiencies in European Congestion Management Proposals*

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Abstract

An efficient congestion management system is a necessary condition to remove obstacles to the cross border trade of electricity in Europe and hence to move towards an internal electricity market. Locational marginal pricing (LMP) is progressively becoming the benchmark of congestion management in the United States. It is conceptually simple, compatible with basic economic theory and physical realities, and effective in practice. Proposals for congestion management in Europe depart in several ways from this benchmark. We discuss these proposals and illustrate some of their inefficiencies. A special emphasis is placed on the restrictions to trade implied by the implementation of zonal approaches.

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Introduction

Three new gas and electricity laws entered into force in the European Union on July 1, 2004 (see DG TREN web site *http : //europa.eu.int/comm./dgs/energy_transport/*). One of them, the Regulation on cross border trade of electricity (Regulation 1228/2003), is intended to enhance competition in the power sector by facilitating cross border trade among Member States. Regulation 1228/2003 principally addresses two issues; namely access to the network and the management of congestion at the interconnection between the Member States. This paper focuses on the latter subject. The content of the Regulation largely reflects the outcome of the work of the Florence Regulatory Forum (see DG TREN web site http://europa.eu.int/comm./dgs/energy_transport/). The Forum began its work in 1998 and has since issued several studies on the two subjects addressed by the Regulation. This paper concentrates on the Forum's proposals on congestion management. It assesses them with respect to the extant literature and international experience.

The conclusion of this analysis is twofold. The two main proposals presented by members of the Forum are quite related to, but still different from, the market splitting approach implemented in the Nordic electricity system, and extensively discussed in the Forum. One of these proposals, namely coordinated auction (ETSO 2001a), is a downgrading of market splitting while the other, namely decentralised market coupling (EuroPex 2003) is, at least in principle, quite close to it. The recent evolution towards a merging of these two proposals (ETSO-EuroPex 2004) goes in the right direction and should be pursued. It has been argued that the meshing of the continental grid makes market splitting or related methods inapplicable in continental Europe(ETSO 2001 b, c). If so, it is urgent to follow the advice of the Commission's Strategy Paper (EC 2004) and to look at the nodal systems of the East Coast of the United States and to the experience with the flowgate model in Texas. These systems may not be as extensively tested (at least for the flowgate system of ERCOT) as market splitting but experience with them is still considerable and positive. Specifically, the recent decision of ERCOT to move towards a nodal system is noteworthy. These methods are likely to provide the additional sophistication to market splitting that the complexities of the continental grid may warrant. International experience also reveals that the separation of the energy and transmission markets that underlies coordinated auction is dangerous. It has proved catastrophic in California (Sweeney, 2002) well before the other causes that led to the meltdown of that system came into play. Last one should also note at the outset that the public documents of the Forum fall short of the level of detail that one would expect from a description of an effective congestion management system.

The paper is organised as follows. Section 1 provides some background on congestion management including a brief recall of its treatment in Regulation 1228/2003. Some simplifying assumptions are presented in Section 2. For the sake of concreteness and clarity the discussion is conducted on a simple example that allows all computations to be verified by hand: it is also presented in Section 2. The rest of the text discusses four congestion management methods. Nodal pricing and market splitting are discussed in Sections 3 and 4 respectively. Decentralized market coupling, which emanates from the association of Power Exchanges is analysed in Section 5. Coordination auction, which originates from the Transmission System Operators is presented in Section 6. Conclusions terminate the paper.

1 Congestion Management

Congestion separates geographic markets into submarkets. Congestion arises from the saturation of transport infrastructure. It may occur in any spatially distributed sector that requires transport facilities. Because one cannot build infrastructures of infinite capacities, congestion is unavoidable but should not be excessive. The frequency of congestion and the expanse of the resulting submarkets depend on both the capacity and the management of the infrastructure. This also applies to electricity, with the additional touch of complexity that this product creates.

Congestion management in electricity is far from a new subject in the academic and professional literature. Its analysis began with Hogan's seminal 1992 paper (Hogan 1992) on nodal pricing (referred to as locational marginal pricing (LMP) in current texts). The subject has since been extensively debated and there is now considerable theoretical knowledge on it. Empirical knowledge is also important. Market splitting, is a simplified form of nodal pricing that was implemented in the Nordic system in 1993 (*http://www.nordel.org/*). New Zealand introduced a first version of nodal pricing as early as 1997. The real development began with the implementation of this method in PJM in 1998 and the progressive adoption of it by the voluntary pools of the East Coast of the United States since (NYISO and ISO NE). The success of PJM has led to its progressive expansion toward the Midwest in the US. This success has also led FERC to make nodal pricing part of its standard market design proposal. As in Europe though, this proposal that aims at a closer integration of the regional electricity markets has encountered strong resistance. Also noteworthy is the implementation of the flowgate model in Texas in 2001 ($http://www.ercot.com/$). While different from nodal pricing, the flowgate system implements the principle of locational marginal pricing.

Congestion management is handled in four articles of Regulation 1228/2003. Article 1 makes "the allocation of available transmission capacities of interconnections between national transmission system" part of the scope of the Regulation. Article 2 provides essential definitions, among them, in paragraph 2(c) a definition of congestion on interconnections that only involves international transactions: "congestion means a situation in which an interconnection linking national transmission networks, cannot accommodate all physical flows resulting from international trade requested by market participants, because of a lack of capacity of the interconnections and/or the national transmission systems concerned". Article 5 imposes general coordination and publication obligations on TSOs in their handling of congestion. It also introduces the notion of Transfer Capacity (paragraphs 2 and 3) on which all the congestion management proposals of the Forum are based (ETSO 2001b). Article 6 sets general principles of congestion management in the European Union. Specifically, it introduces three key requirements, namely "Network congestion problems shall be addressed with non-discriminatory market-based solutions which give efficient economic signals to the market participants and transmission system operators involved" (Paragraph 1). "The maximum capacity of the interconnections and/or the transmission networks affecting cross-border flows shall be made available to market participants, complying with safety standards of secure network operation" (Paragraph 3). Last "Transmission systems operators shall, as far as technically possible, net the capacity requirements of any power flows in opposite direction over the congested interconnection line "(Paragraph 5).

The language of the Regulation only sets general principles. One must thus rely on the work of the Forum to find more specific recommendations. The first publication of the Forum on congestion appeared in November 1999 (ETSO 1999). The paper did not mention nodal pricing even though it was already operating in New Zealand by that time. The paper also examined quantitative allocation methods and some 'market-based' approaches, among them market splitting, and different forms of redispatching. Throughout its work since this first report, the Forum often referred to the very successful organization of the Nordic market as a possible benchmark for Europe. In April 2001, ETSO proposed its coordinated auction method, which we discuss in section 6. We note here that it separates the electricity and transmission markets. A rationale for introducing coordinated auction was that the meshing of the continental grid makes it difficult to apply market splitting. Another justification invokes the differences of electricity systems among Member States and the current impossibility of integrating them. This argument was further elaborated in different papers and led to ETSO's question whether the goal is to integrate the national electricity markets or to simply link them (ETSO 2001c). It concluded the latter. One must wait until the final version of the Commission strategy paper in March 2004 to see a reference to nodal pricing (EC 2004). It is only in 2003 that EuroPex introduced its proposal of decentralisation through market coupling. Like ETSO proposal, EuroPex takes the view that the objective is to link submarkets more than to integrate them (EuroPex 2003). The interesting feature is that EuroPex proposal allows one to overcome the separation between the energy and transmission markets and hence paves the way for a true integration of electricity markets. In other words, even if EuroPex proposes linking markets, it effectively suggests a path towards market integration. This potential seems to have been recognized as recent documents emphasise the need to merge the coordinated auction and decentralised market coupling approaches (ETSO-EuroPex 2004).

2 Assumptions and Example

2.1 Assumptions

2.1.1 Absence of market power with the generators

It is now widely recognized that it is difficult to avoid all exercise of market power in restructured electricity systems. Market power is not necessarily a serious problem (the exercise of some market power is present in most of the economic life) but it can become one when it is abusive. We completely do away with market power in this paper and note in passing that, possibly as a result of both structure and regulatory intervention, the nodal systems of the East Coast of the United States exhibit little market power.

2.1.2 Single settlement system

The Forum never refers to multiple settlement systems. It conducts its discussion on some abstract a-temporal market. We follow the same process and do not refer to a particular temporal organisation of the market. We implicitly assume that we are working with a day-ahead market and do away with all considerations of balancing.

2.1.3 Perfect coordination of TSOs

Article 5 of Regulation 1228/2003 set several obligations of coordination and publication on the TSOs. These will be difficult to enforce: one does not know at this stage how to devise incentives for TSOs to coordinate and the recent explanations of the blackouts all point to the lack of coordination among TSOs. The philosophy of this paper is to identify defects that occur even in ideal situations. We therefore suppose that TSOs over-satisfy the obligations of Article 5. They perfectly cooperate and reveal all the information they have.

2.1.4 Absence of market power by the TSOs

The question of the possible exercise of market power by TSOs is rarely addressed even though the activity of the Federal Cartel Office in Germany indicates that it might be a real problem in some cases. Sticking to the philosophy of only looking at defects that occur even in ideal conditions, we completely neglect the possible exercise of market power by TSOs.

2.2 An example

The example, depicted in Figure 1, is taken from Chao and Peck (1998).

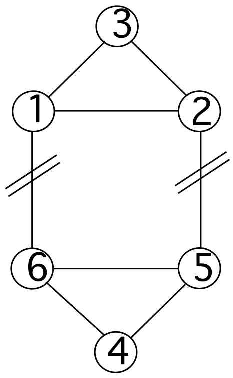

Figure 1: The six node example (// indicates capacity consstrained lines)

The network is lossless; it comprises six nodes and eight lines. Generators are located at nodes 1, 2 and 4; demand at nodes 3, 5 and 6. Marginal cost curves and demand functions at the nodes are of the form $a + bq$ where the coefficients a and b are listed in Table 1.

Node	Linear a	Quadratic b
1	10	0.05
2	15	0.05
3	37.5	-0.05
4	42.5	0.025
5	75	-0.1
6	80	-0.1

Table 1: Marginal costs and demand

All lines have infinite capacities except for the lines (1-6) and (2-5). Line impedances are equal to 1 except for (1-6) and (2-5) that have impedances equal to 2. Load flow equations are modelled by the PTDF coefficients of the lines (1-6) and (2-5). These PTDFs give the flows through lines (1-6) and (2-5) respectively resulting from injections at all nodes of the network and withdrawals at node 6, which is taken as the hub. These are given in Table 2.

Node	Line (1-6)	Line(2-5)
1	0.625	0.375
2	0.500	0.500
3	0.5625	0.4375
4	0.0625	-0.0625
5	0.125	-0.125

Table 2: Power distribution factors, referred to as matrix A

All these data are identical to Chao and Peck (1998).

We use the six-node network in different configurations. A first situation (1) models a single zone pricing system: the prices at all nodes of the system must be equal and redispatching used to counter the flows that, with these equal prices, would exceed the capacities of the lines. The single price zone corresponds to the "coordinated cost +" proposal of the large consumers ($http://www.ifiec-europe.be/elec12.htm$). Two other configurations (2_1 and 2_2) correspond to two-zone models. They differ by the aggregation of the nodes to zones. The last configuration (4) is a four-zone model. The multi-zone configurations are depicted in Figures 2 and 3 respectively.

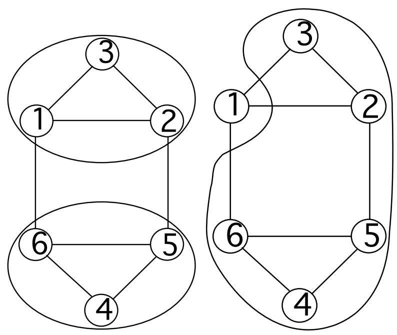

Figure 2: The two zone configurations 2_1and 2_2

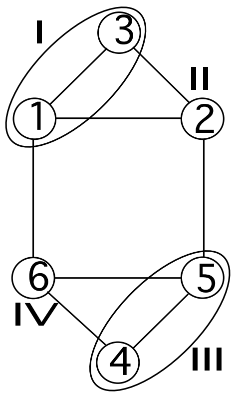

Figure 3: The four zone configuration

Zones I and II respectively contain nodes 1, 2, 3 and 4, 5, 6 in configuration 2_1. The zones are separated by an interconnection composed of interconnectors (1-6) and (2-5) (in compliance with Article 2 of the Regulation, we reserve the word "interconnector" for a line that link regional or national subsystems). Zone I only contains node 1 and zone II contains all other nodes in configuration 2_2. They are separated by the interconnectors (1-6), (1-2) and (1-3). The four-zone configuration is composed as follows: zone I consists of nodes 1 and 3, zone II only contains node 2, zone III comprises nodes 4 and 5 and zone IV is limited to node 6. The zones are connected by six interconnectors (1-6), (1-2), (3-2), (6-5), (6-4) and (2-5). In all cases, intra-zone lines have infinite capacities. This satisfies the commonly accepted, even though violated assumption, that congestion in an integrated European electricity system would only occur at the interconnections. The inadequacy of that assumption should not come as a surprise. The same common wisdom prevailed in the United States before it was disproved by the facts after restructuring. The examples are sufficiently simple for all computations to be verifiable by manual calculation.

The organization of the European system is largely bilateral. Except for Spain, which incentivizes transactions to go through the pool by remunerating them with a capacity payment if they do so, no European market has a mandatory pool. We follow the tradition of the congestion management literature (including the one of the Forum) and disregard unit commitment issues. Pools are then equivalent to power exchanges, which are themselves equivalent to bilateral systems under the assumptions of perfect competition and absence of transaction cost. In other words we assume that centralized and decentralized markets are equally efficient. This assumption is also common in the literature even though particular implementations may lean toward one system or the other. NETA in the UK is probably the most extreme example of the belief in the superiority of bilateral markets. The former Pool expressed the alternative view that centralised markets are better. The systems of the East Coast of the United States and Nordpool offer a centralised market but leave it to participants to decide whether to resort to it or to contract bilaterally. Ideal assumptions such as adopted in the literature and in most the Forum's congestion management deliberations make these differences irrelevant. We work with the pool or bilateral representation depending on the problem on hand.

Economists normally refer to efficiency in order to characterize a market design. This is measured by welfare. We therefore also report welfare information. The Forum never refers to welfare and engineers sometimes see it as an abstract concept. Something else must thus also be reported. The total amount of generated and consumed electricity, the use of the network or of the interconnections, the average electricity price and average congestion cost are probably considered more relevant. We therefore also provide this information.

3 The nodal and flowgate systems

3.1 The nodal and flow gate system: a primer

The nodal system and its flowgate version can be traced to basic engineering and economics. Electrical engineers extensively elaborated, in pre-restructuring days, on the difficulties that Kirchoff laws would create for competitive electricity systems. The response anticipated the question: Boiteux and Stasi (1952) in Electricité de France argued that Kirchoff laws make the price of electricity different at all nodes and that these differences are related by the solution of an optimal power flow problem. This spatial differentiation comes on top of the more common time differentiation of the electricity product that expresses the well-known non-storability of electricity. Electricity therefore consists of a myriad of products differentiated by space and time. The idea of spatial differentiation was extensively elaborated in Schweppe et al. (1988).

Hogan brought it into the more complex world of financial contracts in his seminal paper (Hogan 1992). The subject has received considerable attention in the literature since then. Nodal prices are best illustrated by computing them: this is done in Section 3.3.

The spatial and temporal differentiation of electricity and the numerous markets that it entails are at the origin of various attempts to "simplify" the problem. The flowgate system is one of these proposals (Chao et al. (2000)). The nodal and the flowgate systems have been extensively debated in the US. They share several common points. First, and certainly most important, they are equivalent and maximise welfare under ideal assumptions (e.g. perfect reliability) even if they differ in the real world. Second, they were never discussed by the Forum. Third, both market designs are implemented and have accumulated extensive experience by now. The interested reader is referred to the HEPG web site for academic papers on the subject (*http://www.ksg.harvard.edu/hepg/papers.htm*) and to the sites of the systems implementing either the original nodal model (*http://www.pjm.com/index.jsp*) or its flowgate version (*http://www.ercot.com/*).

3.2 Nodal system in the work of the Forum

The Forum never referred to the nodal and flowgate systems. Only the final version of the Commission strategy paper (EC 2004) recommends considering that method. Still, Europeans are well aware of nodal pricing. As mentioned above, the French electricity sector came up with these ideas well before any talk of restructuring and one can probably trace the first systematic computation of nodal prices to EdF's "Mexico" model in the seventies. More recently England and Wales considered resorting to a flowgate system. Bringing the US debate between the nodal and flowgate models to the Forum would probably have been most useful. Specifically, ETSO's question on whether the goal was to integrate or link national electricity systems alluded to in section 1 can indeed be rephrased in the flowgate language. Because congestion is assumed immaterial inside each control zone but important at the interconnections between the zones, the common wisdom is that one should be satisfied with a system that only manages the interconnections and leaves the internal system untouched. This is restated is flowgate parlance by assuming that the interconnectors are the only "commercially significant flowgates" of the European system. Trying to build a flowgate system for Europe would have gone a long way towards structuring new proposals for congestion management. The Forum avoided that discussion which shall therefore not be elaborated on here either.

3.3 Nodal and flowgate system on the example

Nodal prices are obtained as follows. Take the supply and demand curves of table 1 as offers and bids and compute an optimal dispatch subject to the capacity constraints of lines (1-6) and (2-5). The optimal power flow problem is given in Table 3.

$$
\begin{array}{lll}
\max & \sum_{i \in D}((a_i q(i) + \frac{1}{2} b_i q_i^2) - \sum_{i \in S}((a_i q(i) + \frac{1}{2} b_i q_i^2) & \\
\text{s.t.} & \sum_i A(i,m) q(i) \leq cap(m) & m \in \{(1-6),(2-5)\} \\
 & \sum_i q_i = 0 &
\end{array}
$$

Table 3: Nodal system

The objective function can be interpreted as the total welfare, which is also equal to the sum of producers' and consumers' surplus. The first constraint set represents the limitation on lines (1-6) and (2-5). $A(i,m)$ is the PTDF coefficient of node i and line m. The second constraint expresses the balance of electricity at node 6 (the hub). The dual variable of the balance constraint at node 6 is the system electricity price. The interconnectors (1-6) and (2-5), which are the only lines with limited capacities, can be interpreted as the few "commercially significant flowgates" if one rephrases ETSO's vision (ETSO 2002) in the flowgate language. The dual variables of the line flow constraints are interpreted as the prices of the line services. Local marginal prices at the different nodes can then be derived using these dual variables and the PTDFs. These results are taken from Chao and Peck (1998) and reproduced in Table 4.

3.4 International experience with Nodal and flowgate systems

The nodal system was first implemented in New Zealand in 1997. A more significant move took place in PJM in 1998 when nodal pricing replaced a failed single zone system. The companies that were originally part of PJM had been operating as a tight pool since 1927 which may have

Node	quantity	nodal price	Line	flow on line
1	300	25	(1-6)	200
2	300	30	(2-5)	200
3	-200	27.5		
4	200	47.5		
5	-300	45		
6	-300	50	Welfare	23000

Table 4: Results for nodal pricing

facilitated the inception of the nodal system. PJM recently expanded out of its historic area to several states in the Midwest. PJM's adoption of the nodal system in 1998 was followed by New York (NYISO) in 1999. More recently, in 2003 New England (ISONE) also abandoned a zonal system to turn to the nodal system. Observation shows that except for periods of tight capacities this system behave extremely competitively (see the Market monitoring report on *www.pjm.com*). The flowgate system is implemented in ERCOT since 2001 and works well too. Still, gaming problems (a phenomenon that we do not consider in this paper) has recently led ERCOT to move towards implementing a nodal system by 2007. The experience of that system would be particularly relevant for appraising ETSO's vision fully.

4 Market splitting

4.1 Market splitting: a primer

The nodal and flowgate market architectures acknowledge that injections and withdrawals in different nodes of a control area do not have the same impact on network flows. This justifies nodal prices. It is commonly objected that this reasoning suffers from two drawbacks: it leads to too many and hence illiquid nodal submarkets. It also renders the global market unnecessarily complex because of the need to coordinate too many submarkets. In other words, complying with the economic reality would be self-defeating. The dispute on this point is long lasting and remains unsettled. The standard response to this criticism is to aggregate nodes into zones: this increases the number of traders in each zone and enhances liquidity. It also reduces the number of submarkets that have to clear and hence simplifies trading. This requires some means to resolve possible zonal congestion. Experience shows that these can exacerbate market power. We do not discuss market power in this paper and have accordingly assumed unlimited capacities of intra-zone lines. Focussing on inter-zonal trade, injections and withdrawals at the nodes of a zone are assumed to take place at a representative zonal node and be paid or charged a zonal price. Zones are connected by interconnections that account for the transfer possibilities between zones. Trade takes place between zones connected by interconnections. Only zonal energy and the transfer capacity of interconnections are priced. We shall see that there are different ways to aggregate nodes in zones. Given the zones, there are also different ways to compute zonal prices. There are thus different versions of market splitting. Whatever the chosen implementation however, market splitting, like nodal pricing, simultaneously clears the energy and transmission markets. The following illustrates the possible diversity of market splitting implementations. Consider the first two-zone configurations (configuration 2_1 in Figure 2) of our test example. This corresponds to the standard North-South model discussed in the academic literature (e.g. Joskow and Tirole 2000) and depicted in Figure 4.

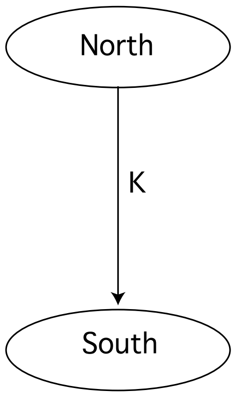

Figure 4: The North-South model

It can be seen as a stylisation of many European situations: Belgium-Netherlands in Benelux, France-Germany in the foreseen regional sub-markets of the Commission strategy paper (EC 2004), and Italy-continental Europe in the European market are all examples of two zone models connected by interconnectors in the sense of Regulation 1228/2003.

4.1.1 Ideal market splitting

In two papers devoted to the Nordic system, Bjørndal and Jornsten (2001) and Bjørndal et al. (2003) consider an "ideal" implementation of market splitting whereby a supranational TSO solves an optimal power flow, subject to the additional constraints that nodal prices in a given zone are equal. This problem is stated in Tables 5 and 6 for configurations 2_1 and 2_2 respectively.

max	$\sum_{i\in D}((a_i q(i) + \frac{1}{2}b_i q_i^2) - \sum_{i\in S}((a_i q(i) + \frac{1}{2}b_i q_i^2)$	
s.t.	$\sum_i A(i,m)q(i) \leq cap(m)$	$m \in \{(1-6),(2-5)\}$
	$\sum_i q_i = 0$	
	$p_i = price_1$	$i \in \{1,2,3\}$
	$p_j = price_2$	$j \in \{4,5,6\}$

Table 5: Two zone model with exact network representation, configuration 2_1

max	$\sum_{i\in D}((a_i q(i) + \frac{1}{2}b_i q_i^2) - \sum_{i\in S}((a_i q(i) + \frac{1}{2}b_i q_i^2)$	
s.t.	$\sum_i A(i,m)q(i) \leq cap(m)$	$m \in \{(1-6),(2-5)\}$
	$\sum_i q_i = 0$	
	$p_j = price_2$	$j \in \{2,3,4,5,6\}$

Table 6: Two zone model with exact network representation, configuration 2_2

These models have the same objective function as the model of table 3 and their two first constraints are also identical. The third and fourth constraints in the model 2_1 of table 5 require that the nodal prices are equal in each zone. The third constraint in the model 2_2 of table 6 requires that all nodal prices of zone II are equal. One will see later that the formulation of zonal pricing through such two zonal models may hide considerable difficulties when some nodal consumption or generation falls to zero in a zone at the prevailing price. These difficulties also illustrate the type of intractable problems that one can encounter in single zone markets such as proposed in the coordinated Cost + of the large consumers (see $http : //www.ifiec-europe.be/$) or by the Brattle group (Brattle 2003). These are discussed in Section 4.3. Note that the two zone systems depicted in Figure 2 and modeled in Table 5 and 6 retain the original network. They do not assume that the two zones are linked by some interconnection for which electrical characteristics need to be found.

max	$\sum_{i\in D}((a_i q(i) + \frac{1}{2}b_i q_i^2) - \sum_{i\in S}((a_i q(i) + \frac{1}{2}b_i q_i^2)$	
s.t.	$\sum_i A(i,m)q(i) \leq cap(m)$	$m \in \{(1-6),(2-5)\}$
	$\sum_i q_i = 0$	
	$p_i = price_1$	$i \in \{1,3\}$
	$p_j = price_3$	$i \in \{4,5\}$

Table 7: Four zone model with exact network representation

4.1.2 Second best market splitting

The ideal approach uses the supply and demand curves of the agents and the true physical description of the network in order to find the zonal prices. An alternative implementation of market splitting (hereafter referred to as ”second best”) first replaces the original six-node model by an aggregate two-node model connected by an interconnection for which one constructs synthetic physical characteristics. This alternative approach is important in practice because both the decentralized market coupling and the coordinated auction methods discussed in Sections 5 and 6 also assume an aggregate network. We develop the idea at the occasion of market splitting but also use it in the following sections. Consider the configuration 2_1 of Figure 2 and the associated two-node model of Figure 4. We need to find electrical characteristics of the interconnection joining these nodes (in this case the aggregate of lines (1-6) and (2-5)). The physical characteristics always encompass a “transfer capacity” as required by Article 6, Paragraph 1 of the Regulation. Depending on the adopted electrical model, one may also construct the PTDFs of the interconnection.

The construction of an aggregate network raises problems even in such a simple example. Take the two-zone model of Figure 4 as a two-node model where the node South is the hub. The associated PTDFs are reported in Table 8.

Node	Line (N-S)
North: 1,2,3	1
South(hub)	0

Table 8: Power distribution factors in the two node network

Denote by A^{ns} the PTDF of the North South network computed in Table 8. The mathematical program that computes the market equilibrium for the configuration 2_1 is stated in Table 9.

max	$\sum_{i\in D}((a_i q(i) + \frac{1}{2}b_i q_i^2) - \sum_{i\in S}((a_i q(i) + \frac{1}{2}b_i q_i^2)$	
s.t.	$\sum_i A^{ns}(i)q(i) \le K$	A^{ns} are the North-South PTDFs
	$\sum_i q_i = 0$	

Table 9: Two zone model with aggregated network representation

This formulation conforms to the definition of congestion of Regulation 1228/2003: congestion on the interconnection can only occur because of an international transaction (between North and South). But it does not conform to physics: all transactions whether intra-zonal or inter-zonal use the lines (1-6) and (2-5) with the result that they can contribute to a congestion of one of these lines and hence of the interconnection. Neglecting these zonal transactions in the definition of congestion makes the law at variance with physical realities.

4.1.3 On zone definition

ETSO and Nordpool commonly describe market splitting by supposing that some supranational TSO first computes a system price as if there were no line constraint. If the obtained flows exceed existing capacities, this supra-national TSO progressively splits the market to search for flows that can be accommodated within existing capacities. This principle is illustrated in Section 4.3. Market splitting can be implemented with fixed and variable zones. The Nordic system began with variable zones before switching to fixed zones. Changing zones, as illustrated by the possibility of choosing configurations in Figures 2 and 3, may be seen as a complication. One may thus decide to fix the zones. Bjørndal and Jornsten (2001a) extensively elaborate on the question of zonal decomposition.

4.2 Market splitting in the work of the Forum

The Forum paid considerable attention to market splitting from the very beginning of its work. It is a market-based method and hence fulfills the requirement of Regulation 1228/2003. It has a long record of success in the Nordic countries. ETSO saw difficulties in a full transposition of market splitting to the European system because of the meshing of the continental grid (ETSO 2001a). This concern can be explained as follows: zones can be constructed in different ways even in a very simple example such as our six-node model where only two lines have limited capacities. The number of possible zones becomes considerable in the meshed part of the continental submarket where many line capacities may be binding. Choosing "good" zones may thus be a difficult and important problem (see Bjørndal and Jornsten 2001a). Freezing the zones is no solution because "good" partitioning may change with time. These concerns were expressed in ETSO (2001a) and ETSO (2001c) while ETSO (2004) (Reconciliation of market splitting with coordinated auction concepts) explains how market splitting can be mixed with coordinated auctions that we discuss in section 6. Notwithstanding the interest for market splitting, the Forum's public documents on the subject remain rather general. They use the same type of stylised examples as academic papers without providing systematical studies on real systems, something that ETSO is in a unique position to conduct.

4.3 Market splitting on the example

4.3.1 Ideal Market Splitting

Consider first the market equilibrium when the line constraints are ignored. Table 10 reports the generation and consumptions at the different nodes with the resulting flows on lines (1-6) and (2-5) which both exceed the limit of these lines. Generators 1 and 2 essentially produce for the demand nodes 5 and 6 with the result that the capacities of both interconnectors are

Node	quantity	price	Line	flow on line
1	500	35	(1-6)	434.37
2	400	35	(2-5)	415.63
3	-50	35		
4	0	42.5		
5	-400	35		
6	-450	35		

Table 10: One Zone

considerably exceeded. Generator 4 is driven out of the market because it is too expensive at this common price of 35. This solution is clearly infeasible for the real network.

It is easy to see the origin of the infeasibility. The single price condition forces all consumptions and generations to be determined via the supply and demand functions by that single price. The balance between supply and demand determines that price. There is no reason why the obtained quantities would satisfy the constraints on the lines. The large industrial users propose to accommodate these congestions by redispatching. This requires calling upon the high cost generator. It is remarkable that there is no single price solution that accommodates the line constraints and hence that there is no pure market based system that can manage congestion in the single price organisation. In other words, any single price that induces generator 4 to produce also induces generators 1 and 2 to drastically increase their production. At the same time the higher price leads to a collapse of demand in node 3, 5 and 6 with the result that it is impossible to balance supply and demand. The pure single zone configuration is thus infeasible. This idea has already been elaborated in Hogan (1999) with respect to the single zone system operated in PECO in 1997. The system also ran into an infeasible situation because the participants learned how to game it with the result that there was no resource left for redispatching. The same infeasibility is obtained here without gaming: requiring a single prize and accommodating the constraints of the line as demanded by the large industrial customers ($http://www.ifiec-europe.be/$) and sometimes by the Brattle group (Brattle 2003) amounts to solving an overdetermined system. It cannot be done.

Suppose one abandons the idea of a single price and is willing to accept two prices. Following the scheme discussed in Section 4.1, the Supra-TSO selects one of the violated lines and splits the market in two parts around this line. Recall that we simplified the discussion by only supposing constraints on the interconnectors. The market can thus only split on interconnectors in our example. Starting from the results of table 10 the Supra-TSO can select line (1-6) or line (2-5) to partition the market. Suppose that it selects line (1-6). There are still different possible partitionings of the nodes into zones. One possibility (maybe most natural from a geographic point of view) is to group nodes 1, 2 and 3 in zone I and nodes 4, 5 and 6 in zone II. This is configuration 2_1 in Figure 2. It is also possible to select the configuration 2_2 where zone I only comprises node 1. The only criterion is that the nodes separated by a line at capacity be in different zones. That is, node 1 should be in zone I and node 6 in zone II. Suppose the TSO envisages splitting the market using these two configurations 2_1 and 2_2 of Figure 2. We simulate this cases, using both Bjørndal and Jornsten ideal method and the second best approach.

Consider first configuration 2_1 in the ideal method, that is after imposing that the prices in each zones be equal. The results of model 2_1 are depicted in Table 11.

Node	quantity	price	Line	flow on line
1	343.75	27.19	(1-6)	200
2	243.75	27.19	(2-5)	181.25
3	-206.25	27.19		
4	212.50	47.81		
5	-271.88	47.81		
6	-321.87	47.81	Welfare	22806.64

Table 11: Two Zones, configuration 2_1

As one could expect, prices are different in the two zones. There is a loss in welfare compared to the nodal system (from 23000 to 22806.4). Total consumption remain at 800.

Consider configuration 2_2. As for the single zone problem, there is no solution because the capacity of line (2-5) is exceeded. One would thus need to split zone II in two other zones. This small example illustrates Bjørndal and Jornsten concerns about the choice of the zonal decomposition. It also confirms ETSO's arguments that meshing increases the number of possible partitioning beyond what is practical to compute. This indicates that the selection of the partitioning of the set of nodes into zones is indeed important.

Table 12 reports the result of the four zone configuration depicted in Figure 3.

Node	quantity	price	Line	flow on line
1	322.94	26.15	(1-6)	200
2	298.62	29.93	(2-5)	194.50
3	-227.06	26.15		
4	183.49	47.09		
5	-279.13	47.09		
6	-298.85	50.11	Welfare	22943.23

Table 12: Four Zones

Welfare improved and is now closer to the result of zonal pricing. Note however that market splitting will never end up in the four-node configuration depicted in Figure 3. Indeed the lines separating zones I and II, and III and IV have unlimited capacity. Node 2 will thus never be split from nodes 1 and 3. Similarly node 6 will never be split from nodes 4 and 5. But nodes 2 and 5 could be split apart if line (2-5) were saturated.

Finally, note that the Bjørndal and Jornsten formulation depends on price sensitive demand. If the demand is fixed and we solve a minimal cost dispatch problem we can't set the prices equal in each zone anymore.

4.3.2 Second best market splitting

We now return to the North-South two zone network. This requires to construct a representation of the aggregate network. Even in the simple example it is not clear how to determine the capacity of the interconnection between North and South. If we take the capacity that is used in the nodal model (400) as the capacity of the interconnection, and the PTDFs given in Table 8, then the solution found with the aggregate network will be infeasible for the real network. In other words, Article 6, paragraph 2 of the Regulation will be violated: the maximum capacity of the interconnections cannot be made available. Therefore, the capacity K has to be chosen on a lower, 'safer' value. If we set $K = 381.25$, which is the capacity that is used in the ideal market splitting, we get the same result; but that implies that one calculates the ideal market splitting first.

Alternatively, since we already know that in the nodal model only the interconnector (1-6) is congested we could set the capacity of the interconnection (North-South) equal to the capacity of the line (1-6). But then one has to choose the PTDFs for this interconnection. Assuming, as in the definition of congestion of the Regulation, that intra-zonal flows do not affect the interconnector one might believe that using the maximal PTDF for the exporting North (Table 13) will give a feasible and safe power flow, possibly at the cost of a loss in social welfare (see Table 14).

Node	Line (N-S)
North	0.625
South	0

Table 13: Power distribution factors in the two node network

In our example consumption remains at 800 but there is a drastic loss of efficiency in generation. We comply with safety standard but a cost of productive efficiency.

But even this approach cannot always guarantee the necessary safety standards. Indeed, intra zonal flows do affect the interconnectors. Suppose, for the sake of illustration, that we change the network configuration and set the capacity of line (1-6) and therefore North-South to 20. Then, the resulting flow using the maximal PTDF from Table 8 are infeasible for the real network (Table 15) because one did not account for the impact of intrazonal transactions on the congestion of the interconnection.

Node	quantity	price	Line	flow on line
1	323.33	26.17	(1-6)	169.38
2	223.33	26.17	(2-5)	150.62
3	-226.676	26.17		
4	253.33	48.83		
5	-261.67	48.83		
6	-311.67	48.83	Welfare	21480.83

Table 14: Result for the North-South network with 'safe' PTDFs

Node	quantity	price	Line	flow on line
1	227	21.37	(1-6)	26.37 (inf)
2	127.33	21.37	(2-5)	6.63
3	-322.67	21.37		
4	445.33	53.63		
5	-213.67	53.63		
6	-263.67	53.63		

Table 15: North-South, with 'safe' PTDFs and line capacity 20 on (1-6)

4.4 International experience with Market splitting

Market splitting has been in operation in the Nordic market since 1993. Leaving aside the possible complexity of transposing it to the rest of Europe due to the meshing of the grid, its interest is considerable. It is close to nodal pricing but it is not a standard market design in the quite demanding sense of FERC's proposal. It is a minimal common design requirement that allows some diversity of submarkets. Specifically, methods for managing intra-zone congestion, intra-day trading and balancing could remain different among the different Member States. It is remarkable though that the system progressively moves toward more harmonization and integration with time. In other words, even though it did not start with a standard market design, Nordpool standardises its regional markets more and more.

5 Decentralised market coupling

5.1 Decentralised market coupling: a primer

The principle of decentralised market coupling is at first sight, at the opposite of market splitting. Market splitting separates an integrated market when it cannot do otherwise. Decentralised market coupling does not have an integrated market to start with, but only a set of independent markets that it wants to link. The reality is that the proposals are quite close and in some cases identical. This can be understood as follows.

Assume, following the philosophy of EuroPex, that there is a power exchange in each zone where all electricity generated and consumed in the zone is traded. Zonal generation and consumption do not necessarily balance, with the result that there can be import and export into and from the zone. We refer to these as net import (import if positive, export otherwise). Each power exchange clears at a price that depends on net import. The clearing price, when seen as a function of the net import, defines a true inverse demand curve for net import. Imports and exports are traded via the interconnections: this is where the coupling of the decentralised markets represented by the power exchanges takes place. In contrast with market splitting, decentralised market coupling therefore considers two clearing processes on the energy market: one zonal process clears the energy market in each zone; a second interzonal market clears energy between zones. This differentiation of the clearing processes is rooted in a vision similar to the one expressed by ETSO (2002) and confirmed in Article 1 of the Regulation. There is indeed no view of an integrated market in the proposal of decentralised market coupling. Like ETSO, EuroPex takes it for granted that the differences between Member States are such that it is impossible to integrate the individual markets; the best one can do is to link them. EuroPex infers from these differences that a coupling algorithm, let alone a single clearing process for both national and international exchanges of electricity, is difficult to construct. It therefore suggests informal iterations between the different zones based on the demand curves for net import but does not give details.

We take the view that this weak attitude is not fully convincing and that the proposal can be pushed much further. A minimal harmonisation of products is necessary for trading between zones. We assume enough harmonisation to make products tradable and suppose that the proposed iterations required to balance the demand for net import in the different zones can be cast in an algorithm. The discussion of EuroPex (2003) indeed recalls similar considerations made before at the Energy Information Administration of the US Department of Energy for linking different models. These led to now well-established and powerful algorithms and we assume that the same can be done here. These equilibrium algorithms can easily be made equivalent to a welfare optimization over the whole area.

It remains to specify the system used for trading electricity between the different national submarkets. Like the second-best form of market splitting, decentralised market coupling EuroPex (2003) assumes an a priori given zonal decomposition of the global market linked by an aggregate network. EuroPex (2003) leaves it to the Transmission System Operators to construct this aggregate network. As discussed at the occasion of market splitting, it can be a set of zones linked by interconnections endowed with standard electricity characteristics (topology, PTDFs and transfer capacity). More simply the interconnections can be characterized by transfer capacities only without any notion of PTDF. This is referred to as the pipeline model.

It is conjectured that this approach is equivalent to market splitting if the zonal decomposition and the representation of the network were the same. Assume for the sake of comparison with market splitting, that the products have been sufficiently harmonised to be tradable. The outcome of decentralised market coupling is then as follows. Traders bid on the sole energy market of their power exchange; there is a single price and net import in each zone. This is similar to market splitting. The methods may differ by their zonal decomposition: market splitting splits an integrated market insofar as necessary to account for the saturation of the lines. Decentralised market coupling starts with a priori given zones. Depending on the representation of the network, decentralised market coupling may thus lead to different zones that are linked by non-saturated interconnectors. This may give more zonal prices than market splitting. This will be illustrated in Section 5.3. But suppose that the zonal decompositions are the same and that the interconnectors that are saturated in market splitting are also saturated in decentralised market coupling and conversely. Then, the two methods would give the same results at least if the zonal networks are identical. We shall go further into that discussion in Section 5.3.

EuroPex's proposal assumes that all electricity traded in the zone goes through the PXs. This assumption may look heroic but is not a real issue. One can easily dispense with it by combining implicit and explicit auctions. Suppose, as it is indeed the case in most Member States and in Nordpool and the pools of the East Coast of the United States, a mix of organized (PX) and decentralized (bilateral transactions) markets. Suppose as before that each PX constructs its demand curve of net import. Suppose also that the bilateral transactions bid for transmission services. One can then construct a procedure whereby both the PX and the bilateral transactions go to the transmission system operators to acquire transmission services. This would lead to a single more complex equilibrium (or welfare maximisation) algorithm. But this is perfectly doable. It is important to note that both demand for net import by the PX and demand for net import from bilateral transactions need to compete for the resources of the transmission facilities. One should not a priori allocate a fraction of these resources to one or the other as has sometimes been proposed. Again, all this is perfectly doable, but for the sake of brevity, is not elaborated on here.

5.2 Decentralised market coupling in the work of the Forum

Decentralised market coupling was introduced by the association of Power Exchanges to the 2003 meeting of the Forum. It is sketched in EuroPex (2003) but the presentation remains far from a precise description of a method. Analogy with former work in the Energy Information Administration at the US Department of Energy suggests that it would not be difficult to develop the proposal into a fully documented approach. The proposal chronologically came after ETSO's coordinated auction that we discuss next but is based on the same vision: the variety of market architectures in the Member States is not amenable to the integration of these markets. The closeness between this method and market splitting has been recognized in passing by some authors (see e.g. Gilbert et al (2004)). As we argued above the method is not fully identical to market splitting, as there are differences in the zonal decomposition.

5.3 Decentralised market coupling on the example

Consider the decomposition of the six-node network in the two-zone configuration 2_1. Assume that there is an exchange in each zone and that the products traded in these exchanges are standardized enough to be tradable between the two zones. EuroPex's proposal assumes that each power exchange computes a demand curve for net import as a function of its clearing price. This is easily done in the two-zone example by proceeding as follows. Assume a given clearing price in a zone. One computes the excess demand/supply; this excess demand/supply is the net import at that clearing price. Doing this for zones I and II one finds the expression listed in Table 16 with $io(j)$ being equal to -1 or $+1$ depending on j being a generator or consumer.

$$\boxed{t_i(p_i) = \sum_j io(j) \max\{\tfrac{(p_i - a_j)}{b_j}, 0\} \quad j \in \text{ zone } i.}$$

Table 16: Import/export demand curve of zone i

The second step of the approach is to clear the market between zones I and II. One could in principle associate nodal injections and withdrawals to the clearing price in each zone and hence rely on an exact representation of the network. This would be an ideal version of decentralised market coupling analogous to the ideal version of market splitting. This is not what EuroPex proposes when assuming that the import and export into and from a zone take place at some representative node of the zone. Assuming the same representation of the aggregate network as in the second best market splitting of Section 4.1.2 we need to find the equilibrium between zones I and II when the maximal quantity through the interconnection is set to a safe value (below 381.25, the flow from North to South in the corresponding model for ideal Market splitting). The model representing the combination of these two market clearing processes is shown in Table 17 for the North-South configuration.

The result is the same that we found in market coupling. As argued above, the zones are the same and they are separated by a saturated interconnection. The representation of the aggregate network (which here boils down to the transfer capacity) is also the same. The two methods give identical results.

max	$\sum_{i\in D}((a_i q(i) + \frac{1}{2}b_i q_i^2) - \sum_{i\in S}((a_i q(i) + \frac{1}{2}b_i q_i^2)$
s.t.	$t_i(p_i) = \sum_j io(j)q_j \quad j \in$ zone i
	$\sum_i t_i = 0$
	$A^{ns}t \leq K$
	$q_j = \max\{\frac{(p_i - a_j)}{b_j}, 0\} \quad \forall j \in i, i = I, II$

Table 17: Decentralized market clearing

We argued in the discussion of market splitting that the four-zone configuration would never occur in market splitting because the lines that link zone II to all its neighbours in the four-zone example are never saturated. Zone II, which can be on its own in decentralised market coupling will always be part of another zone in market splitting. Consider the application of decentralised market coupling to the four-zone case and the problem of finding the equilibrium between these zones. This requires an aggregate network that links these zones. As we shall discuss in the next section, ETSO faces the same problem in its coordinated auction. We discuss the problem of the construction of this network in the following.

The aggregate network model of the four-zone problem is depicted in Figure 5. At least two methods can be thought of for constructing it. One relies on the pipeline model: interconnections are only modeled by transfer capacities. The other is more sophisticated and also endows these interconnections with physical characteristics like aggregate PTDFs. We illustrate the difficulties raised by this latter method, knowing that even though looking a priori simpler, the pipeline model is more complex to calibrate and more susceptible of erratic results. Note that this discussion will be reused in the presentation of coordinated auction. Consider the PTDF constraints of the nodal model (e.g. Table 3). Their use lead to the true physical limitations that bear on the flows in the network. The four-zone configuration supposes that injection and withdrawals at nodes 1 and 3 can be aggregated into a net export of zone I and that injections and withdrawals at nodes 4 and 5 can be aggregated into a single import zone III. The vectors of PTDF factors of 1 and 3 in zone I are not identical and hence any aggregation will be an approximation. The same is true for the injections and withdrawals at nodes 4 and 5 in zone III.

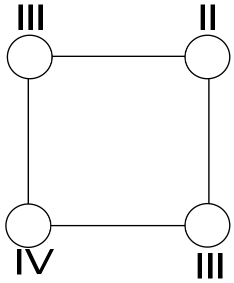

Figure 5: The aggregate 4 node network

We showed in Section 4.3.2 that zonal transactions could contribute to congestion on interconnections. We also recalled before that this phenomenon is not captured in the definition of congestion appearing in Article 2, paragraph 2 c) of the Regulation. Suppose that we abide to the definition of congestion stated in the Regulation and only consider international transactions in the computation of the PTDFs of the interconnections. One might choose the maximal (nodal) PTDFs for exporting and the minimal PTDFs for importing zones, in the belief that these PTDFs will then guarantee flows that are feasible in the real network. For the given example we can report that the 'safe' PTDFs in Table 18 lead to a feasible outcome (reported

Node	Line (1-6)	Line(2-5)
I	0.625	0.4375
II	0.500	0.5
III	0.0625	-0.125

Table 18: Four Zones with 'safe' PTDFs

in Table 19). One obtains an increase of consumption from 800 to 816 compared to the nodal pricing result. But this increase comes at the price of a welfare decrease from 23000 to 22827 since generation and consumption are not efficiently allocated.

At least the flows are feasible. But this is just luck. As we have already seen in Section 3 in the North -South example 'safe' PDFs are not safe at all.

Node	quantity	price	Line	flow on line
1	315.1	25.76	(1-6)	197.34
2	310.65	30.53	(2-5)	193.52
3	-234.9	25.76		
4	190.17	47.25		
5	-277.46	47.25		
6	-303.57	49.64	Welfare	22827.36

Table 19: Four zones with 'safe' PTDFs

5.4 International experience with Decentralised market coupling

Decentralised market coupling admits the coexistence of two types of institutions, namely Power Exchanges and Transmission System Operators. It does not merge them into a single entity. This coexistence is the common wisdom in the whole of Europe except in the Nordic market. In the Netherlands, the Transmission System Operator, TenneT, owns the Power Exchange (APX) but their operations remain separated. In contrast, the pools of the East Coast of the United States integrate the Power Exchange and Transmission. NETA in England and Wales also fully separates transmission and power exchanges, but that system does not face the problem of market integration: England and Wales is an integrated market to start with and it is the role of NGT to keep it so. England and Wales are about to integrate with Scotland under a single price regime. This may be more difficult to manage and will undoubtedly be a most interesting experience to watch.

One of the claimed reasons for the success of the restructuring of the East Coast is that the power exchange and the transmission are integrated in a Pool that accounts for system constraints in electricity pricing. This principle was abandoned in California by first separating power exchanges from the transmission operator and second limiting the interactions between both to a few iterations. EuroPex's proposal can lean towards one or the other solution. If the iterations between the PX and the TSOs are taken seriously, then the system will be equivalent (up to the differences between the products traded between Member States and the simplification of the network) to an integrated system. This still allows for an uncertain outcome but one can hope that it should not cause too many difficulties. In contrast, if this interaction between the power exchanges and the transmission system operators is limited to a few iterations as was the case in California and if these are conducted in a more or less ad hoc way, then the same difficulties with congestion management that occurred in California might also happen in Europe. The vagueness of the current text from EuroPex and the absence of any concrete indication of the quality of the aggregate network on ETSO's part make it impossible to conclude. Europeans can still choose to go one or the other direction.

6 ETSO's coordinated auction

A coordinated auction is most naturally presented by referring to bilateral transactions between generators and consumers. We accordingly reformulate the reference nodal pricing model by explicitly introducing these transactions using the formulation of Olmos and Perez Arriaga (2004) (Table 20). Let I and II respectively denote the two zones North and South. $I-II$ denotes the set of balanced energy transactions between I and II; p^{I-II} is the vector of balanced transmission transactions $I-II$ and b^{I-II} expresses the vector of values of these transactions.$PTDF_m^{I-II}$ and cap(m) are respectively the PTDFs and the capacities of the interconnectors joining zone I and II. This notation applies to both the original and aggregate networks.

$$\boxed{\begin{array}{ll} \max & b^{I-II}p^{I-II} \\ & PTDF_m^{I-II}p^{I-II} \leq cap(m) \end{array}}$$

Table 20: Nodal Pricing based on bilateral contracts

6.1 Coordinated auctions: a primer

A coordinated auction is a further and major departure from the nodal model. Like decentralised market coupling, a coordinated auction assumes that the architectures of the electricity markets of the Member States are so different that integration is not possible. It therefore also limits itself to linking zonal markets without attempting to integrate them (ETSO 2001a). Another common point between the proposed coordinated auction and decentralised market coupling is that both proposals are based on a zonal representation of the network (even though this is not intrinsically necessary). The main distinction between the two methods is the following: in contrast with decentralised market coupling, a coordinated auction goes through a single sequence of two markets; the market for transmission opens first and closes before the opening of the energy market. Assuming ideal conditions that make centralised and decentralised markets equally efficient, a coordinated auction would be equivalent to decentralised market coupling if one expands that single sequence into several iterations between the transmission and energy markets. Both methods would then maximise welfare given the possibilities offered by the aggregate network. Both methods would also coincide with nodal pricing if they adopted a full nodal network instead of a zonal aggregation of it. The coordinated auction as currently presented suffers from two weaknesses that we briefly discuss.

6.1.1 The perfect anticipation assumption

A coordinated auction assumes that traders can value transmission services ex ante before going to the energy market. We first explore this assumption, assuming that one is working with the full network (original nodes and lines). Consider first the simplified case where one assumes constant marginal costs and willingness to pay. Further assume that traders behave competitively and hence that they demand transmission services at a flat rate up to the upper bound of that transaction: a trader simply submits a price for a transmission service between an origin and a destination. The value of that bid is simple to compute for constant marginal cost and willingness to pay. Take a transaction from generator node 1 to the demand node 6 as the example. The value of the transaction is equal to the (constant) willingness to pay in node 6 minus the (constant) cost at node 1. Assuming perfect information, one can construct a program referenced to as the Perfect Coordinated Auction (PCA) that models the bids of the traders to an organization conducting the transmission auction. Using the notation of Olmos and Perez-Arriaga (2004) and letting i and j refer to nodes and (i, j) to an individual transaction between i and j, this can be formulated as shown in Table 21. The numerical discussion is conducted in Section 6.3.1.

This program is identical to the nodal pricing program in table 3, obtained after making

max	$\sum_{(i,j)} B^{i,j} p^{i,j}$	
s.t.	$\sum_{(i,j)} A[(i,j),m] p^{i,j} \leq cap(m) \quad m \in \{(1-6),(2,5)\}$	
where	$A[(i,j),m] = A(i,m) - A(j,m)$ is the PTDF coefficient of the bilateral transaction (i,j)	

Table 21: Perfect coordinated auction

the same simplifying assumption of constant marginal costs and willingness to pay. The perfect coordinated auction would thus be entirely equivalent to nodal pricing. The separation of the energy and transmission markets is thus irrelevant in this case and ETSO's coordinated auction fully justified in terms of economic efficiency. ETSO's vision claims would then offer the additional advantage that a coordinate auction can still be implemented when nodal pricing cannot because of the different markets architectures in the zones.

This equivalence is much more difficult to obtain under the more realistic assumption of non-constant marginal cost and willingness to pay. The valuation of transmission transactions is indeed much more complex. Taking again transactions from 1 to 6 as an example, a trader cannot value this transaction without also knowing how much generator 1 already sells to 2 and 5 and what consumer 6 already receives from 2 and 4. The question is whether, as sometimes argued in the literature (Gilbert et al. (2004), Ehrenmann and Neuhoff (2003)) traders can anticipate this. The standard economic assumption of rational expectations assumes that they do but this requires an extraordinary rationality: what generator 1 sells to 2 and 5 and what consumer 6 receives from 2 and 4, indeed depend on the price the traders will be charged from transmission, which is exactly what one wants to find. A perfect coordinated auction with non-constant marginal costs and willingness to pay therefore assumes that traders can solve the full problem of nodal pricing before they submit their bids for transmission. This is certainly not what ETSO wanted to assume when it submitted its proposal. It is also quite in variance of the justification for the coordinated auction proposal by Olmos and Perez-Arriaga (2004).

6.1.2 The impact of the aggregated network

A further problem of the coordinated auction proposal arises from its implementation in a zonal configuration. The recourse to a simplified representation of the network in a coordinated auction is here justified on the ground that traders want to stay away from the intricacies of the electrical network when they trade electricity. Needless to say the TSOs need to deal with these intricacies and TSOs are using a full model of the network, not a zonal one. The differences between these two models have already been elaborated upon before.

One then obtains the new model Simplified Coordinated Auction (SCA) as stated in Table 24 for the transmission auction, with A^{ns} being again the zonal PTDFs (see Section 6.3.2. for a justification of the decomposition of the table in two parts). The recourse to two representations of the network introduces an asymmetry of behaviours that suggests that the assumption of perfect anticipation is untenable or at least difficult to justify. Traders reason on the basis of the simplified SCA model while TSOs reason on the basis of the full model. They are bound to differ at some points except if the simplified model is perfectly equivalent to the full model. This will also be elaborated in the example.

6.2 Coordinated auction in the work of the Forum

ETSO's coordinated auction was initially proposed in April 2001 (ETSO 2001a). It is built on the vision that integration of the electricity markets of the Member States is not possible given their present architectures and therefore the best one can hope for is a market coupling approach (ETSO 2002). The proposal has now been around for several years without much new concrete being reported about it, except for the 2004 meeting of the Florence Forum where it was proposed to merge it with EuroPex decentralised market coupling. Still, it is the first market-oriented proposal submitted to the Forum.

6.3 Coordinated auction: the example

6.3.1 The perfect anticipation assumption

In order to grasp the possible impact of the perfect anticipation assumption, consider the simplification of our six-node example already alluded to in section 6.1 where we neglect the linear part of the marginal cost and demand functions of Table 1. In other words, we assume that generators 1, 2 and 4's marginal costs are respectively 10, 15 and 42.5 and consumers 3, 5 and 6's willingness to pay are 37.5, 75 and 80 respectively, independently of the amount produced or consumed. As an example, the value of a transaction between generator 1 and consumer 6 would be thus 80-10 = 70 under this assumption. In order to bound the Perfect Coordinated Auction problem we also assume that quantities at generation and demand nodes are limited to twice the values found in the solution of the nodal system (see Table 3). This gives us the supply and demand data reported in Table 22.

Node	Linear a	Quadratic b	upper/lower bound c
1	10	0	600
2	15	0	600
3	-37.5	0	-400
4	42.5	0	400
5	-75	0	-600
6	-80	0	-600

Table 22: Modified supply and demand data

The values of the bids obtained in the Perfect Coordinated Auction are listed in Table 23.

Transmission line	value	capacity used (Solution table 21)
1-3	27.5	0
2-3	22.5	400
4-3	-5	0
1-5	65	400
2-5	60	0
4-5	37.5	200
1-6	70	0
2-6	65	50
4-6	42.5	200

Table 23: Value of the balanced transaction

One easily checks that the solution of the nodal pricing model would, on the basis of the supply and demand data of Table 22, and the result of the perfect coordinated Auction on the basis of the same data, be identical. The traders only need to know market data and can dispense with the intricacies of the network. Traders will thus receive transmission rights that are fully compatible with the energy trade of nodal pricing.

Suppose now that one considers the original data given in Table 1. Assume that one still works with the real network and traders can simulate the calculation of the TSO, but that the latter did not provide the full information. Specifically, suppose the capacity of line (1-6) is changed to 180 and traders do not know. Recall that the solution of the nodal system consists of generation of 300, 300 and 200 at nodes 1, 2 and 4 and consumptions 200, 300 and 300 at nodes 3, 5 and 6. Suppose the traders, unaware of this change, misjudge the outcome. The TSO reveals to the arbitragers the share of the capacity bids that complies with the real limits of the network. Since there is only one congested line the arbitragers can update their informations about the network and reach an equilibrium in the second iteration. Needless to say, the correction process would require more iterations and be possibly more intricate in a more complex case. But this can be done without requiring the traders to simulate the computation of the TSO on the real market. The important remark is thus that traders do not need to know the exact characteristics of the network because of this tatonnement process with the TSOs. In contrast this tatonnement cannot proceed and traders are bound to misjudge the result when, as in the Coordination Auction proposal, there is a single iteration. Information need then be perfect in the Coordinated Auction and traders need to be able to perform the comptation of the TSO. In contrast imperfect information can be corrected through iterations in decentralised Market Coupling.

6.3.2 Network aggregation

Consider now the case where the TSO aggregates the network and fully reveals the information related to the aggregate network to the traders. We take the simplest two-zone model where the PTDF from zone I to II is equal to 1. The TSOs need only publish a single number, namely the transfer capacity. In order to fix ideas, we assume that TSOs have foreseen a distribution of generation and consumption in line with the result of the nodal pricing computation. This implies a flow of 400 MW from North to South, which is thus also taken as the transfer capacity. Traders use this information to try to anticipate the result of the energy market. Assuming the traders' anticipation capability, their problem can be formulated as a social welfare maximisation problem with respect to the capacity constraints. This problem is depicted in Table 24 using, Olmos and Perrez-Arriaga's notation. It is separated in two parts. The coordinated auction is summarized in the optimization problem in the upper part of Table 24 for fixed transmission prices B. The anticipation of the B is given in the lower part of Table 24. Needless to say both most be solved simultaneously if anticipation is perfect.

Simultaneous solution of	
max	$\sum_{(i,j)} B^{(i,j)} t^{(i,j)}$
s.t.	$t_i = \sum_j io(j) \max\{\frac{(p_i - a_j)}{b_j}, 0\} \quad j \in$ zone i
	$t_i = \sum_j t^{(i,j)}$
	$\sum_i t_i = 0$
	$A^{ns} t \leq 400$
and	
	$B^{(i,j)} = p^j - p^i$
	$q_j = \max\{\frac{(p_i - a_j)}{b_j}, 0\}$

Table 24: Simplified coordinated auction

Suppose that traders are perfectly rational as assumed in Gilbert et al. (2004) and Ehrenmann and Neuhoff (2003)but that they reason with respect to the aggregate network to value their bilateral transaction. They implicitly compute the equilibrium between the North and the South zone using the PTDF of Table 8 and a line capacity of 400. This problems solves the equilibrium problem with the second-best network and leads to prices of 27.50 in North and 47.50 in South. They end up with marginal valuations of their bilateral transactions as shown in Table 25. It is also easy to see, referring to section 3 (market splitting) that this is a version of the second-best market splitting where the transmission capacity on the interconnection is 400. But

Transmission line	value
4-3	-20
1-5	20
2-5	20
1-6	20
2-6	20

Table 25: Value of the balanced transaction

we had seen in section 3 that the transmission flows under market splitting in the exact network is only 381.25. Traders will thus be allocated less than the announced capacity. This reveals an incoherence that goes beyond a simple inefficiency in the use of the network. It implies that a positive price is charged for a transfer capacity that is not fully used. In other words, the market is split into two zones on the basis of the real network while it turns out to be a single zone in the aggregate network when the announced transfer capacity is 400. This incoherence is due to the asymmetry of reasoning between the TSO and the traders. This duality of reasoning can be interpreted in terms of Article 6, paragraph 3 of the Regulation: the TSOs reason with nodal pricing in order to maximise the capacity of the interconnector. But the use of the aggregate network forces the traders to value their transactions from zone to zone instead of from node to node. The result is, that the maximal capacity announced by the TSOs will not be reached.

The situation may be worse. Even though the maximal capacity of 400 is not fully utilized, the demands of the traders may be infeasible in the real network. This may occur as follows: because one is in a two-zone network, the anticipation of the market equilibrium gives a single price in zone I, and a single price in zone II and a transmission price equal to the difference between the two. Because all traders value their transactions between zones in the same way, the TSO will allocate the 400 MW indifferently between them without knowing in advance, at the time of allocation their injection and withdrawal point. Suppose, that the 400 MW are allocated in equal part between (1-5), (1-6), (2-5) and (2-6). Injection points are now revealed to the TSOs that verify whether they meet the real constraints of the network. In this case 200 MW flow on

(1-6) and 200MW flow on (2-5). Now we clear both markets separately, assuming that the flows in the zone do not affect the interconnectors I-II. Because zonal transactions exist and indeed have an impact on the interconnectors, the resulting generation/consumption (Table 26) violates the capacity on (1-6).

Node	quantity	price	
1	350	27.5	203.125 (inf)
2	250	27.5	156.25
3	-200	27.5	
4	200	47.5	
5	-325	47.5	
6	-275	47.5	

Table 26: After clearing of the power exchanges in North and South

Now suppose in order to proceed further that the 400 MW are allocated in non-equal part between (1-5), (1-6), (2-5) and (2-6), if for instance 150MW are allocated on (1-6), 50MW on (1-5) and 100 on (2-5) and (2-6). This flow pattern violates the capacity limit of the real network even if the intra-zonal flows are neglected. The reason is very simple. An allocation of transmission capacities that meets the constraints of the aggregate network does not necessarily meet the constraints of the real network. And there is no way, except if traders have full knowledge of the real network and reason with it that they can anticipate the constraints of the real network in the coordinated auction conducted on the simplified network. In other words, one cannot remove the incoherence by assuming that the TSOs perfectly anticipate the reasoning of the traders on the aggregate network. One needs instead to assume that the traders anticipate the reasoning of the TSOs on the real network. This unravels all the claimed advantages of coordinated auction. The practical implication is that, given the large variety of possible generation patterns within zones, the computation of the transfer capacities of the interconnections has to be extremely conservative and therefore the network utilisation extremely inefficient.

6.4 Summing up

A coordinated auction assumes that traders can value the transmission and energy transactions separately. The value of a transmission transaction requires knowing the willingness to pay of the consumers and the marginal cost of the suppliers. These depend on the outcome of the energy market which itself depends on the trading rights assigned by the transmission auction. Some papers that concentrate on the analysis of the strategic behaviour of generators (Gilbert et al. (2004), Ehrenmann and Neuhoff (2003)) use a rational expectation argument that traders can perfectly anticipate the result of the global energy and transmission market. The same assumption applied in a context where there is no market power would go a long way towards justifying the coordinated auction method. The above loop in the reasoning suggests that this assumption of rational expectation is quite demanding and difficult to satisfy. This conclusion is supported by other analysis of the literature. Specifically, Harvey et al (1996) argue that competitive generators and traders face uncertainty about prices in the energy market when deciding on their bids for transmission markets and might therefore buy an inappropriate amount of transmission rights. Neuhoff (2003) gives empirical support using the example of the German-Dutch interconnection. The assumption of rational expectation can be alleviated under some condition; but all of them are much more demanding than what the Forum supposes. Take the simpler nodal case where the problem of the network aggregation is absent. Suppose first that one takes the usual assumption of perfect information in a very strong sense: traders and TSO have the same information on demand and supply functions as well as network characteristics. Both groups can then perform exactly the same type of computation and can simulate a nodal pricing system. This is obviously not what the Forum wants to assume. A coordinated auction is proposed because traders do not want to deal with the intricacies of the network. An alternative, much more interesting proposal is to assume that traders submit bids that reflect their valuation of transactions as function of the quantities of transmission services or conversely. In other words, traders would be able to say: assume that I have to pay so much for going from this node to that node, this is how much of that transmission service I demand. These are conditional bids. This backward induction reasoning is common in sequential equilibrium problems. But conditional bids are much more complex than assumed in coordinated auctions: they would indeed express the demand for different transmission services as a function of several prices on the interconnections. One does not need to go that far provided one considers iterations of the type envisaged by decentralised market coupling. This also does not require traders to anticipate the price of the transmission transactions. But this is also much more than ETSO's proposal and would in any case require substantial developments. The only possible conclusion is that, without any of these assumptions, traders are bound to err in the valuation of their transaction. This may have a more or less important impact depending on the accuracy of the forecast.

7 Conclusion

Regulation 1228/2003 can be implemented in a hard or soft sense. Coordinated auctions as discussed in the public documents of the Forum are resolutely of the soft type. Decentralised market coupling is harder. More importantly, it has the potential to integrate the energy and transmission markets, therefore paving the path to a consistent system. Second, difficulties can be expected from the use of the aggregate network. One should expect that simulation studies would unveil the difficulties. The real danger is in adopting simplifications that help to achieve a political compromise, but are justified neither in physics nor in economics.

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