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Electricity modelling:
Market power and the relevant market

Professor Yves Smeers
and
Andreas Ehrenmann
Franziska Holz
Graziano Abrate
Jürgen Apfelbeck
Matteo Di Castelnuovo
Paula Ferreira
Karen Freund
Till Jeske
Nenad Keseric
Andras Kiss
Thilo Krause
Florian Leuthold
Rocío Moraga
Carlo Obersteiner
Giorgia Oggioni
Piotr Pałka
Marcelo Saguan
Laura Segafredo
Andreas Semmig
Dalius Tarvydas
Hannes Weigt

Market power and market architecture are closely related and still are often treated separately. We argue that the market architecture affects the size of the relevant market and therefore the reference for the evaluation of market power. We use the Benelux market as a case study to test the impact of nodal pricing, market splitting and market coupling on the relevant market.

1 Introduction

Within the European Commission, DG Energy defines the market architecture of the European electricity system, among which cross border trade. DG Competition takes care of the market structure in general. This dichotomy of competences also applies to the restructured electricity system.

We argue that the market structure and market architecture are closely related and should not be looked at separately. As a side result we examine the impact of the different congestion management schemes on the usage of the interconnectors.

1.1 The Internal Electricity Market

The progressive opening and integration of electricity markets in Europe will also be obtained through increased trading of power between Member States. Market participants (generators, traders and consumers) that want to trade need access to the transport system whose physical capacity however is limited.

This means that either existing networks must be upgraded, especially with reference to cross-border links or that the current available transmission capacity must be efficiently allocated, which is the topic of the ongoing discussion of congestion management.

At the European level, Regulation 1228/2003 focuses on access to the network and on the management of congestion between Member States. This law, which entered into force on 1st July 2004, is mostly the result of the work carried out within the Florence Regulatory Forum, which had started in 1998.

The topic of congestion management is regulated by four articles[1]. Article 6 represents the most relevant one for the purpose of this report, as it defines the general guidelines for congestion management of cross-border trading in the European Union. In particular, it refers to the necessity of solving “network congestion problems with non-discriminatory market based solutions which give efficient economic signals to the market participants and transmission operators involved”. Furthermore the same article requires that “transmission system operators shall, as far as technically possible, net the capacity requirements of any power flows in opposite direction over the congested interconnection line”. At the same “the transmission network affecting cross-border flows shall be made available to market participants, complying with safety standards of secure network operations”.

1.2 The issue of Market power

One possible definition of market power, and the one that is chosen as relevant for the discussion which follows, is “the ability of a firm to raise price above some competition level, the benchmark price, in a profitable way” (Motta 2004). The problem of market power in the European electricity industry context is an issue that currently draws considerable attention. The integration of national electricity systems into a single internal European electricity market is not progressing well, with the result that the level of competition in the sector remains unsatisfactory. One possible explanation of why this is the case is the still high concentration in the generation segment in most European countries or regions, together with the fact that some of the specific characteristics of the electricity

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[1] Article 1, 2, 5 and 6.

industry can enhance the impact of such high concentration. Thus, economists, regulators and competition authorities are interested in analyzing market power issues in electricity.

Having or exercising market power?

A typical question that arises with market power is the difference between having and exercising market power. This distinction is crucial, depending on the type of analysis we want to do and the type of policy measure that we want to implement. On the one hand, studying the exercise of market power (ex-post analysis) considers the comparison of some actual outcomes of the market (e.g. market price) with some counterfactual data (e.g. marginal cost). On the other hand, studies considering the ability to exercise market power (ex-ante analysis) are used to evaluate the effectiveness of ex-ante remedies (e.g. divestiture, virtual auctions, etc.).

Regardless of the type of analysis one wants to carry out, a methodology to measure the capability to exert market power is needed.

How can market power be assessed?

Traditional measures for evaluating the capability of exercising market power seem not to be sufficient in electricity (e.g. concentration index, Hirschman-Herfindal-Index etc.). Experience has revealed that market power in electricity markets could occur even with low concentration. This is the case when the system is tight and all equipments of firms are needed to serve demand. In this situation, even a very small company could raise the price by withholding production (concept of “pivotal” firm or pivotal plant).

As mentioned above, a common methodology for (ex-post) measuring of the exercise of market power is comparing the market price with the short run marginal cost of the system (Borenstein et al. 2002). If the price is higher than marginal cost, this could prove the exercise of market power. However, a key problem is that computing the short run marginal cost in the electricity industry is not an easy, maybe not even a feasible task. Some of the factors that complicate marginal cost computations are for instance: the existence of start up cost, minimal run up and shut down constraints, network constraints, etc. This has been well documented in [Ranjaraman et al. 2003].

Another common methodology to measure the exercise of market power is the use of imperfect competition models (mostly Cournot models). In this type of models, some assumptions are made concerning the strategic behaviour of agents and then the results of the model are compared with the current market behaviour (Bushnell, Mansur and Saravia 2005). This kind of model could also be used to evaluate the capability of market agents to exercise market power (without any reference to real behaviour).

In order to capture reality, market power models should consider all submarkets composing the electricity market. The electricity market is composed of several submarkets: electricity as the “commodity” plus the markets for ancillary services such as transmission, reserves, etc. Accounting for these submarkets increases the complexity of modelling (non-convex problems can arise) and forces us to make certain assumptions of agents’ strategic behaviour (sometimes asymmetric and difficult to justify) for these new markets. Experts in this kind of modelling tell us that the results of the models depend strongly on behavioural assumptions that are difficult if not impossible to verify (Neuhoff et al. 2005). Since these assumptions can be widely and equally chosen, the models become highly unreliable and hence useless for taking important regulatory decisions.

In conclusion, experts have not yet come to an agreement on the optimal methodology to measure market power, which is needed by competition authorities and regulators. In this paper a very simple methodology (SSNI – Small but Significant Non-transitory Increase of price) is proposed, which is related to the definition of the relevant market. The SSNI test also called the “test of the hypothetical monopolist” tests whether an agent can profitably maintain a modest (5%) increase of its price. We apply this test to explore the relevant geographic market of electricity generators.

The question

Regulation 1228/2003 requires reducing congestion through market mechanisms while the issue of market power is addressed in another legal context, i.e. competition law. It follows that, since the regulation of congestion management and market power have not been included in the same legal framework, it becomes very difficult to understand whether a different market design for cross border trade may have an effect on the capability to exercise market power by some of the agents.

Therefore, the purpose of this report is to assess the relationship between different market architectures and the potential exercise of market power in the European electricity market.

2 Market Architectures

Congestion arises from the saturation of transmission infrastructure and creates externalities. Different market architectures (market designs) can be implemented in order to deal with congestion (and externalities). Not all market architectures have equal efficiency results [Ehrenmann and Smeers 2005a]. In this section we describe briefly three different market architectures: nodal pricing, zonal pricing and market coupling.

Nodal pricing

In the old days of the regulated market the aim was to produce and to deliver the demanded energy at least cost. The system operator calculated therefore an optimal power flow problem of the system under the given capacity and network constraints (Kirchhoff laws).

Nodal pricing builds on the same idea with the difference that a system operator now tries to maximize social welfare by finding the right quantities and location for generation and consumption. If transmission capacity is binding at some line, prices in each node are calculated with reference to a price in a hub node and plus the contribution of each node to the congestion.

Zonal pricing

Detractors of nodal pricing systems commonly resort to two types of arguments: the creation of too many submarkets and the problem of illiquid nodal submarkets. The standard response is simply to aggregate nodes into zones, therefore increasing the number of traders for each submarket. Injections and withdrawals at the nodes of a zone are assumed to take place at a representative zonal node and be charged the same zonal price. Basically, the only difference with nodal pricing is that some prices are constrained to be equal. There are of course different ways one can aggregate nodes, and usually they follow a geographical criteria. Since the number of markets is lower than in the nodal case, and only are a limited number of prices can send the right economic signals, the efficiency of zonal pricing is lower and leads to a decrease of total welfare.

The mathematical computation is similar to the one used for nodal pricing: one maximizes the welfare function subject to the capacity constrains of lines. The difference is that one adds additional constraints requiring the nodal prices to be equal in each zone. The system retains the original network.

Flow based market coupling

Flow based market coupling was introduced by the association of Power Exchanges to the 2003 meeting of the Florence Forum. It is sketched in [EuroPex (2003)] but the presentation remains far from a precise description of a method.

Flow based 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.

Flow based market coupling assumes a unified representation of the grid where zones are connected by aggregated interconnecters. The proposed mechanism consists of iterations between Power Exchanges and Transmission System Operators: Even though this mechanism is not yet clearly specified it is easy to see that an ideal implementation of it amounts to nodal pricing where the nodes are replaced by zones and the lines by the aggregate interconnectors.

3 The Case study

Description of the network models

We use an aggregated network representing the Benelux countries and their neighbours, Germany and France, for which data is available.[2] The original network shown in figure 1 consists of 15 nodes in four countries which are connected by 28 lines. Ten of these lines are trans-border lines that connect Germany to the Netherlands (2 lines), the Netherlands to Belgium (3), Belgium to France (3) and France to Germany (2). Supply and demand are located at all of the nodes in Belgium and the Netherlands, but only at nodes D and F in Germany and France. The remaining German and French nodes are passive nodes.

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[2] http://www.electricitymarkets.info/modelcomp/

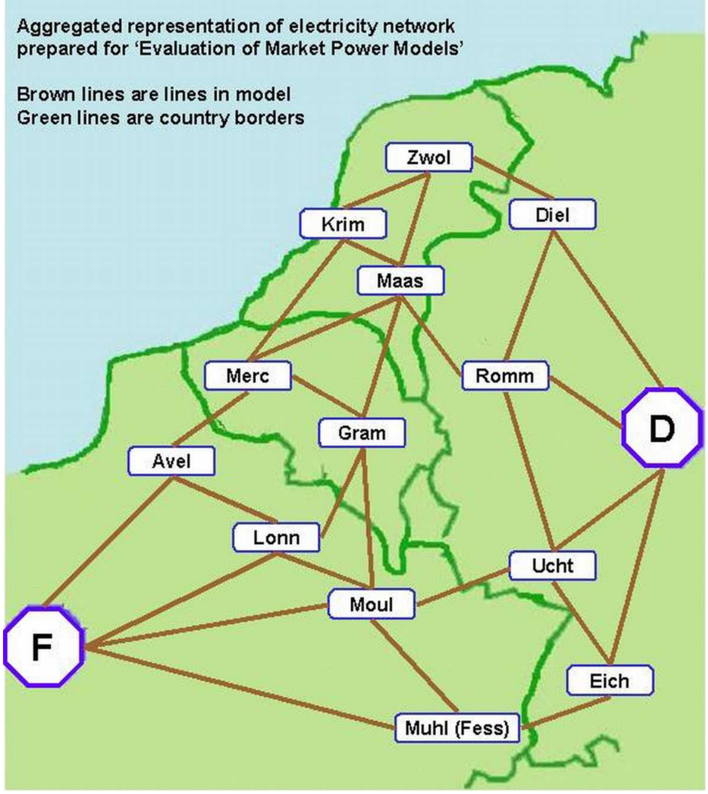

Figure 1. Original network topology as used for the nodal pricing and market splitting approach.
Source: ECN (http://www.electricitymarkets.info/modelcomp/).

Flowgate	Reactance	Max Capacity [MW]
AVEL_LONN	22,2	2762
D_DIEL	45,9	20000
D_EICH	45,9	20000
D_ROMM	45,9	20000
D_UCHT	45,9	20000
DIEL_ROMM	69,2	1842
DIEL_ZWOL	12,2	2971
EICH_UCHT	41,3	3329
F_AVEL	45,9	20000
F_LONN	45,9	20000
F_MOUL	45,9	20000
F_MUHL	45,9	20000
GRAM_LONN	45,2	1207
GRAM_MOUL	156,5	267
KRIM_MERC	34,2	936
LONN_MOUL	27,1	1842
MAAS_GRAM	41,8	641
MAAS_KRIM	29,1	1842
MAAS_MERC	61,0	641
MERC_AVEL	55,4	898
MERC_GRAM	31,1	1842
MOUL_MUHL	38,2	3329
MUHL_EICH	11,5	1282
ROMM_MAAS	28,3	896
ROMM_UCHT	43,0	1842
UCHT_MOUL	25,4	1326
ZWOL_KRIM	33,1	1842
ZWOL_MAAS	50,0	1842

Table 1. Line parameters in the original network model.

4 Findings

The preliminary results reported here touch upon two key issues for the development of an internal European Electricity Market. The first one emphasizes the use of more efficient methods to deal with transmission constraints. The second one is the importance of the designs of cross border trade on the possibility of firms to exert market power. Both factors are extremely important for the organization of cross border trade. A better utilization of transmission infrastructure improves both competition between market players and general market efficiency.

The findings are described in two parts. The first covers the impact of the congestion management scheme on the utilisation of the transmission lines; the second part reports the results of applying the first iteration of the SSNI test for estimating the size of the relevant market to the case study network.

4.1 Different market designs and their impact on line utilisation

According to Directive 2003/54/EC and especially the Regulation (EC) 1228/2003 of the European Parliament and of the Council of 26 June 2003 a better utilisation of the transmission network should enhance competition within the internal electricity market.

Article 6 of the Regulation 1228 on conditions for access to the network for cross-border exchanges in electricity emphasises that the maximum capacity of the interconnections should be made available to all market participants ensuring a large level playing field for electricity trading. On the other side, the second important prerequisite is to ensure that the safety standards for lines within transmission networks affecting cross-border flows should be fulfilled.

With respect to these two important issues introduced in European law, we test the transmission capacity utilisation within the different market designs for cross border exchange of electricity. The level of utilization might serve as indicator for the adequacy of each market architecture. For comparison we propose the following methodology:

1) Find the equilibrium for each market architecture by solving the equivalent optimisation problem (there is always an optimisation problem that is equivalent to the equilibrium problem in the cases considered here; more specifically, we optimise social welfare subject to a series of constraints such as the network topology);

2) Observe the resulting generation and consumption dispatch for each market architecture;

3) Disaggregate generation and consumption and transfer it to the original nodes;

4) Compute the line flows according to the dispatch obtained for each market architecture using the full network representation;

5) Compute the utilization (load) of each transmission line as a quotient of line flow and available transmission capacity.

We illustrate our methodology using the example of flow-based market coupling. In a first step, the market equilibrium is computed using the aggregated network shown in figure 3 of Appendix A (one node representing each country, four interconnections). The equilibrium is determined by an aggregated generation and consumption level for each country, satisfying the aggregated network constraints. We then disaggregate generation and consumption and assign it to the original nodes in the full network representation. We then use the disaggregated generation and consumption to compute line flows, and thus, capacity utilization in the original network.

The utilisation of transmission lines is represented in figure 2 as a percentage of the obtained power flows at peak demand divided by the available transmission capacity. As can been seen, the utilisation of the transmission lines obtained with the nodal market architecture, at almost all transmission lines, is higher than the one computed with the market splitting or flow-based market coupling design. Thus, nodal pricing leads to a more efficient utilisation of the transmission capacities.

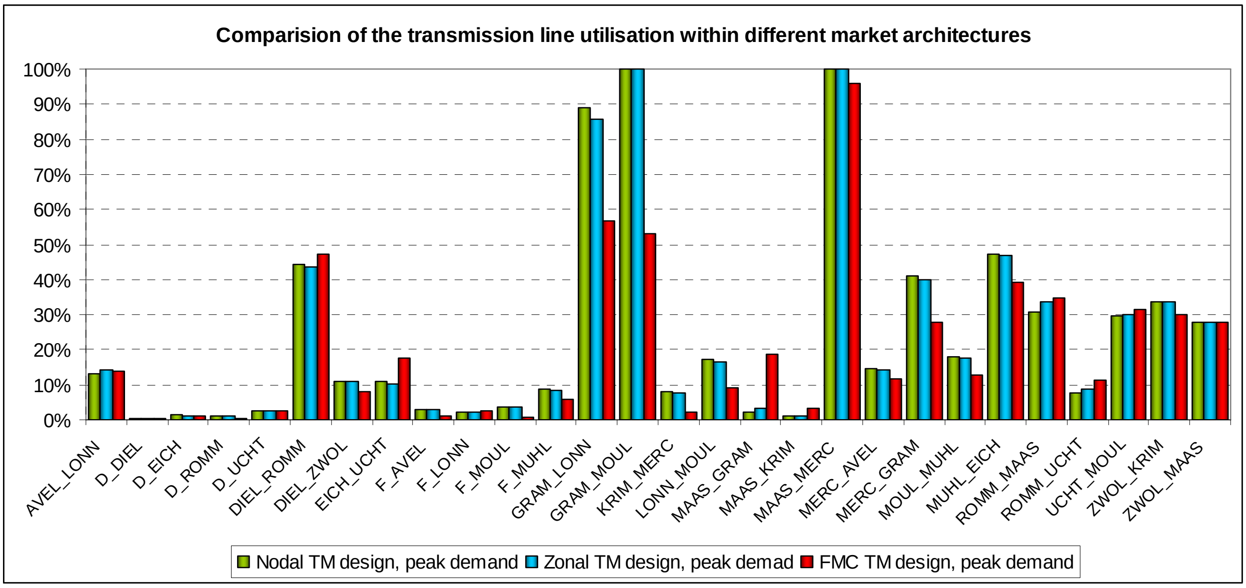

Figure 2. Comparison of the transmission line utilisation within the different market architectures.

4.2 Different market designs and the relevant market

Table 2 represents the results of applying a single iteration of the SSNI test on two major companies of the European power sector. The complete results will be reported in [Ehrenmann and Smeers, 2005b]. Because tightness of transmission capacity is now recognized as an important element of market power in electricity, the test is conducted for two seasons, summer and winter (considered as base load and peak load, respectively).

The first iteration is conducted as follows: Take a company in some season (e.g. in summer). Assume that it increases its bid (price) by the reference 5%. Compute its sales and the price. If the profit increases, then the relevant market of that company in that season is limited to its current geographical coverage. If the profit does not increase or even decreases, then the relevant market is larger.

The test has been conducted for five market architectures, namely pure nodal pricing, market splitting with one, three and four zones and flow based market coupling (see Appendix A for details of the network aggregation).

This single iteration of the SSNI test clearly shows that the relevant geographical market depends on the market design. EdF can raise its profit by increasing its prices by 5% in the base load case under the market design of nodal pricing and market splitting with three or four zones; assuming that all other participants keep their prices constant. When market splitting is performed with one zone all over Europe, EdF is no longer able to exercise market power. This looks like good news; the drawback is that single zone systems imply a drastic decrease of welfare. Similar results could be found when changing prices of E.On. E.On is able to raise its profit in the base-load cases of nodal pricing and market splitting with three zones by increasing its prices. If a market splitting with one or four zones is implemented, no market power can be exercised.

	EdF		**E.On**		**Electrabel**	
+: can exert market power - : cannot exert market power	Base load	Peak load	Base load	Peak load	Base load	Peak load

	(Summer)	(Winter)	(Summer)	(Winter)	(Summer)	(Winter)
Nodal pricing	+	-	+	-	-	-
Market splitting One zone	-	-	-	-	-	+
Market splitting Three zones	+	-	+	-	-	-
Market splitting Four zones	+	-	-	-	-	-
Flow based Market coupling	+	-	-	-	-	-

Table 2: Results of the first iteration of the SSNI test for EdF and E.On (+ indicates that a company profitably increased prices; – indicates that profits either did not increase or decreased).

In peak load (winter) scenarios neither EdF nor E.On are able to exert market power. This is due to the fact that at base load EdF and E.On are operating as marginal generators, in opposition to the peak load case. Needless to say that this result is counter-intuitive but it is nevertheless easy to verify.

The firms RWE, Vattenfall, EnBW are not able to exercise market power. In no case did the simulation of a small increase of prices change profit of the companies; a strong increase caused a profit drop because their marginal generators dropped out. Even the attempt to combine two or three companies with a joint manipulation of their prices could not lead to the ability to exert market power.

5 Conclusions and Specific Policy Recommendation for the EU

It appears quite clear from the modelling results that the organization of cross-border trade may actually have a significant effect on the capability of generators to profitably increase their prices.

Table 2 summarizes the output of the simulation exercise. EdF, for example, sees its profits rise by a very significant amount when increasing its prices by 5% under a nodal pricing scheme, in the base demand (summer) scenario. This also holds when three or four zone market splitting frameworks are in place, as well as four-zone market coupling. Indeed, such results do not come as a surprise when one considers the overwhelming dominating position of EdF in its internal market in France. Interestingly enough, though, the outcome is quite different as soon as a peak-load scenario is considered, probably due to the fact that when capacity is tight, EdF is no longer the marginal generator at its node. Another important player, E.On, seems to follow a quite similar pattern in the ability to exercise market power. Increasing its bids by 5% leads to a 2.2% increase in profits under nodal prices and to a half point increase in profits when a three-zone market splitting is in place, both in low demand conditions. Electrabel appears to have a considerable possibility of abuse of market power only under a single-zone market splitting and at peak-load.

None of the transmission market designs tested here seem to have an effect on the competitive behaviour of EnBW, RWE and Vattenfall. In all simulated cases, the 5% increase in prices was not beneficial for these companies; furthermore, it sometimes led to lower profits compared to the base case. Even coordination between two or more producers to jointly increase their prices in order to realise higher profits, did not result in any ability of these firms to exercise market power.

However, one must point out that the object of our study, i.e. the relationship between cross-border congestion management and the ability to exercise market power, is contingent on the existing network configuration and on the actual market structure (plant capacities and fuel costs), which have been considered as exogenously given in the model described above. This helps explain why the attempt to exercise market power could result in higher profits for the French incumbent generator under a nodal pricing scheme with low demand, whereas a similar effect could be obtained by the dominant generator in Belgium only under single-zone market splitting and peak-load circumstances.

The modelling results seem to suggest that different transmission market architectures have a non-uniform effect on generators' market power, which also vary by each firm's respective area of influence. Therefore, it would be appropriate and effective to address the issues of electricity market design and competition policy in a coordinated and consistent way.

The models also show the difficulties with aggregating the network to a "one country – one node" approach as it is required by ETSO-EuroPEX. The artificial reduction of the network may lead to infeasibilities of line flows once the resulting demand and supply results are reassigned to the nodes of the aggregated network. In practice, this will lead to the necessity of costly redispatch by the European TSO(s).

In conclusion, the findings of this modelling exercise seem to imply that transmission markets should be designed with a careful eye on their competitive effects. Thus, competition authorities, when conducting their analyses, should pay a great deal of attention to the underlying electricity market designs.

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Appendix A

Introduction

The nodal pricing as well as the market splitting design calculations of load flows are based on the "detailed" network model that is the network available from ECN website (http://www.electricitymarkets.info/modelcomp/). Flow based market coupling, as described in the joint ETSO-EuroPEX proposal for *Cross-Border Congestion Management and Integration of Electricity Markets in Europe*[3] relies on a simplified representation of the network.

The aggregate network configuration proposed by ETSO-EuroPEX has the following characteristics:

- There is only one node per country, and
- connections between countries are represented by one single line respectively.

There is an underlying objective that the construction of this aggregate network should also allow for the maximal utilisation of line capacities. The aggregate network topology for the investigated case of the Benelux countries and France Germany is shown in figure 3.

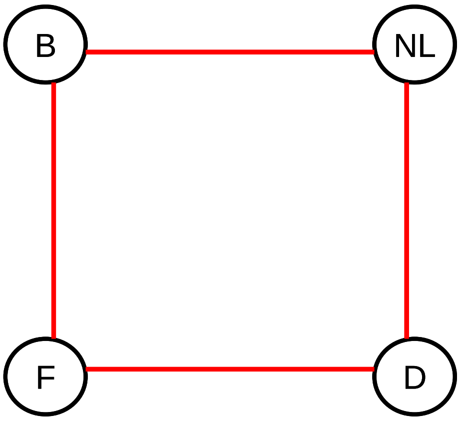

Figure 3. Aggregate network topology used for the flow based market coupling design in the case study.

Derivation of parameters for the aggregate network model

Based on the given data for reactances and maximum capacities for several lines in table 3 for the original network configuration one has to determine the equivalent values for the aggregate network model. When basics of network theory are applied to this problem, it becomes evident that it is not possible to find the perfect equivalent of the original network given the topology foreseen in the ETSO-EuroPEX proposal. Therefore the following approaches used to determine suitable values for reactances and to estimate the power flow limitations for the remaining lines represent only one possible procedure.

Derivation of reactances in the aggregate model

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[3] „Joint Flow-based Market Coupling", a joint ETSO-EuroPEX Proposal for Cross-Border Congestion Management and Integration of Electricity Markets in Europe, Interim Report, September 2004.

When calculating the reactances of the trans-border lines, in a first approach inner-country lines were totally neglected. The reactances of the resulting lines were calculated as the equivalent reactance of the parallel connections of the trans-border lines in the original model, according to the following equation:

$$X_{eq} = \frac{1}{\sum_i \frac{1}{X_i}}.$$

It is evident that this approach only delivers correct results when neglecting inner-country connections between nodes connected to cross border lines. As there are inner-country connections in the original model, this approach only allows to estimate values for reactances for the aggregate topology hoping that the original load flows are not distorted too much.

Derivation of line capacities in the aggregate model

Line capacities for the aggregate model were first estimated according to the following considerations: neglecting inner-country lines, the flows on two parallel lines are related according to the following equation:

$$\frac{P_1}{P_2} = \frac{X_2}{X_1}.$$

Assuming that one of the lines is operating at its capacity limit, the respective flows on the parallel lines can be calculated. This is done for all parallel lines. The “bottleneck line” of every trans-border connection is characterised by the fact that when carrying the maximum flow, flows on all parallel lines do not exceed their respective capacity limit. The capacity of the equivalent line was thus calculated as the sum of the capacity of the bottleneck line $cap_{\lim}$ plus the respective flows on the parallel line(s) i:

$$cap_{eq} = cap_{\lim}\left(1 + \sum_i \frac{X_{\lim}}{X_i}\right).$$

Resulting values for line reactances and maximum capacities

Table 3 summarises the line parameters for the four-node model according to the described approaches above and the according flow factors, respectively.

			Flow Factors			
Flowgate	**Reactance**	**Limits [MW]**	**D**	**F**	**B**	**NL**
D_NL	8.5	2969	0	-0.2753	-0.4264	-0.8375
NL_B	21.5	1864	0	-0.2753	-0.4264	0.1625
B_F	45.9	1945	0	-0.2753	0.5736	0.1625
F_D	7.9	1860	0	-0.7247	-0.5736	-0.1625

Table 3. Reactances, maximum capacities and corresponding flow factors (PTDF-values) for the four node model. Source: Own calculations as described.

Verification of computed parameters

The usability of the calculated parameters was finally tested by inserting the resulting injections and withdrawals into the full nodal model (multiplying the vector of net injections with the PTDF matrix) and verifying whether the resulting flows were feasible under the given line constraints. As expected, this was not the case, so that the calculated line capacities had to be adapted in an iterative trial-and-error-process. The changed parameters were applicable to both the base and peak demand scenario. Whilst the estimated maximum capacities needed to be adapted, the values for the line reactances led to satisfactory results as the distortion of the original line flows was limited. The final setting for the maximum line capacities which was further used for modelling the flow based coupling design is shown in table 4.

Flowgate	Limits [MW]
D_NL	2969
NL_B	1000
B_F	800
F_D	1200

Table 4. Line constraints used for the market coupling case.

The underlying problem briefly indicated above is that by simplifying the electric network in the described way, information about the inner-country load flows and their impact on the system behaviour is lost. The four-node model will never be an exact representation of the full nodal model, only its parameters can be chosen such that for a certain system state (location and level of withdrawals and injections) it produces an output (in terms of line flows) that is similar to that of the full nodal model. In this case, the underlying assumptions according to which the parameters were adapted, was a base load demand scenario and a perfectly competitive electricity market where supply bids equal marginal generation costs. It cannot be guaranteed that the computed parameters do also produce feasible outputs in case that market players exert market power. For a European TSO applying the four node model, in case of line overload, a cost-intensive redispatch of generation capacity would become necessary.

Appendix B

GAMS Code of the used model:

```
$title Infratrain
$OFFSYMLIST
$OFFSYMXREF
option
    limrow = 0,
    limcol = 0;

option iterlim =40000;
option reslim = 40000;
option nlp = conopt;
file relevant_market;
put  relevant_market;

sets i  Nodes /i1*i7/
     j Generator /j1*j9/
     l Powerstation per knot /l1*l6/
     m Lines /m1*m28/
     G1(i) Germany / i1 /
     F1(i) France  / i2 /
     B1(i) Belgium / i3, i6 /
     N1(i) Netherlands / i4, i5, i7 /
     BN1(i) bel+ nyd / i3*i7 /;

set ijl(i,j,l), nijl(i,j,l);

$ontext
j1 E.ON ENERGIE AG
j2 ELECTRABEL SA
j3 ELECTRICITE DE FRANCE
j4 ENBW ENERGIE-VERSOR SCHWABEN
j5 ESSENT ENERGIE PRODUCTIE BV
j6 NUON
j7 RWE ENERGIE AG
j8 VATTENFALL EUROPE AG
j9 Fringe
$offtext

*------------------------------------------------------------------------------


parameter Capkh(m) capacity line m
/m1     2762
```

```
 m2     20000
 m3     20000
 m4     20000
 m5     20000
 m6     1842
 m7     2971
 m8     3329
 m9     20000
 m10    20000
 m11    20000
 m12    20000
 m13    1207
 m14    267
 m15    936
 m16    1842
 m17    641
 m18    1842
 m19    641
 m20    898
 m21    1842
 m22    3329
 m23    1282
 m24    896
 m25    1842
 m26    1326
 m27    1842
 m28    1842/;

parameter Capk(m);
Capk(m)=Capkh(m)/1000;

*--------------------------------------------------------------------------------
* PTDF
*-------------------------------------------------------------------------------

table gamma(m,i) PTDF power transfer distribution matrix for a  flow from node i to the hub via line m
     i1  i2             i3             i4             i5             i6             i7
m1   0  -0.162988114    -0.259716553    -0.392401539    -0.304329192    -0.297676933    -0.584038158
m2   0  -0.017082013    -0.002422548     0.04452692     -0.003472749     0.010395624     0.132053829
m3   0  -0.085581757     0.02566017      0.090035351     0.117234663     0.047656035     0.100117393
m4   0  -0.137334061    -0.293874531    -0.326222374    -0.43374586     -0.30886091     -0.220871546
m5   0  -0.324540714    -0.228888545    -0.130333946    -0.116671058    -0.193677633    -0.08460423
m6   0  -0.101556006    -0.153756332    -0.365554444    -0.12878655     -0.210262572     0.215337236
m7   0  -0.061432128    -0.105960253    -0.026847144    -0.175542679    -0.087414397     0.200624535
```

```
m8   0  -0.009791917    0.00743177      -0.369106189     0.155369218    -0.088625019    -0.100156171
m9   0  -0.06704475     -0.078424999    -0.027369788    0.088979316     -0.209693405    0.016763071
m10  0  -0.121929522    -0.328841555    0.043406459     0.146362927     -0.097956884    0.063146089
m11  0  -0.111347922    -0.146324562    0.265339367     0.026582668     -0.298887591    0.115181065
m12  0  -0.032399121    -0.288443185    0.112145728     0.022201644      0.279965059    0.052043618
m13  0  -0.145993552    0.063693624     0.125823851     0.09336034       0.211453945    0.079900518
m14  0  -0.135479458    0.271917704     0.104712684     0.116138224      0.118450325    0.078450645
m15  0  -0.018849185    0.110797556     0.050839503     0.052426347      0.06355785     0.036739063
m16  0  0.042891351     -0.008972898    0.056295567     0.034648348      0.105549602    0.033259317
m17  0  0.117068721     0.185932783     0.118743441     0.108854487      0.169212377    0.081175971
m18  0  0.052523264     0.100716047     0.067161561     0.067010692      0.084309558    0.050751811
m19  0  0.375137092     0.217520339     0.151042092     0.145253853      0.199784487    0.110485995
m20  0  0.046957978     -0.012768405    -0.023905932    -0.03056961      -0.014327304   -0.025598493
m21  0  0.188884903     -0.072666522    -0.069528284    -0.058711991     -0.105904343   -0.046641201
m22  0  0.209656827     -0.077012022    -0.04226481     -0.041932085     -0.05478755    -0.030533991
m23  0  0.278844441     0.032874253     0.027912563     0.022400916      0.045216964    0.017441008
m24  0  -0.180069321   -0.262137929    -0.347873071    -0.307800565     -0.287280027   -0.451982325
m25  0  -0.205833805   -0.265791813    -0.280713943    -0.313038448     -0.271600499   -0.252807982
m26  0  -0.285916934   -0.241780309    -0.196463364    -0.203336111     -0.227006364   -0.159123131
m27  0  0.322613828     0.116804292     0.083880531     0.07824316       0.115474929    0.059734184
m28  0  -0.328179114   -0.230288745    -0.174948025    -0.175823463     -0.214111791   -0.136084488;
*--------------------------------------------------------------------------------
* generation capacity
*--------------------------------------------------------------------------------

*   D        F        GRAM      KRIM     MAAS      MERC       ZWOL
table capg1(j,i)
    i1       i2       i3       i4       i5       i6        i7
j1  8409     0        0        76       0        0         0
j2  0        0        3451     16       0        2749      549
j3  54       68602    0        0        0        0         0
j4  3313     49       0        0        0        0         0
j5  0        0        0        1071     66       0         0
j6  0        0        0        123      0        0         0
j7  5208     0        0        0        0        0         0
j8  2100     0        0        0        0        0         0
j9  7827     4572     415      385      22       274       40;
table capg2(j,i)
    i1       i2       i3       i4       i5       i6        i7
j1  8454     0        0        873      0        0         0
j2  0        0        679      15       0        901       2688
j3  0        6667     0        0        0        0         0
j4  3435     0        0        0        0        0         0
j5  0        0        0        230      1072     0         0
```

```
j6  0       0       0       568     0       0       0
j7  11639   0       0       0       0       0       0
j8  6041    0       0       0       0       0       0
j9  18180   2748    25      457     235     552     111;
table capg3(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  5844    0       0       385     0       0       0
j2  0       0       134     63      0       1994    0
j3  0       6701    0       0       0       0       0
j4  719     0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       1729    0       0       0
j7  3383    0       0       0       0       0       0
j8  681     0       0       0       0       0       0
j9  8265    2309    494     1171    172     67      906;
table capg4(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  310     0       0       0       0       0       0
j2  0       0       19      0       0       148     0
j3  0       530     0       0       0       0       0
j4  186     0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       0       0       0       0
j7  77      0       0       0       0       0       0
j8  350     0       0       0       0       0       0
j9  683     578     119     13      0       0       0;
table capg5(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  230     0       0       0       0       0       0
j2  0       0       37      0       0       114     0
j3  0       409     0       0       0       0       0
j4  210     0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       0       0       0       0
j7  70      0       0       0       0       0       0
j8  136     0       0       0       0       0       0
j9  783     154     9       0       0       0       0;
table capg6(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  0       0       0       0       0       0       0
j2  0       0       0       0       0       0       0
j3  0       0       0       0       0       0       0
j4  0       0       0       0       0       0       0
j5  0       0       0       0       0       0       0
```

```
j6  0      0      0      0      0      0       0
j7  0      0      0      0      0      0       0
j8  0      0      0      0      0      0       0
j9  0      0      28     0      0      0       0;

parameter capg(j,i,l), anwesend(j,i);

capg(j,i,'l1')=capg1(j,i)/1000;
capg(j,i,'l2')=capg2(j,i)/1000;
capg(j,i,'l3')=capg3(j,i)/1000;
capg(j,i,'l4')=capg4(j,i)/1000;
capg(j,i,'l5')=capg5(j,i)/1000;
capg(j,i,'l6')=capg6(j,i)/1000;

loop(l,
anwesend(j,i)$capg(j,i,l)=1;
);
*---------------------------------------------------------------------------------
* Prices
*---------------------------------------------------------------------------------

*   D      F      GRAM     KRIM    MAAS     MERC      ZWOL
table ca1(j,i)
    i1     i2     i3     i4     i5      i6      i7
j1  6.39    0      0      9.23    0       0       0
j2  0      0      7.51    9.76    0       6.73     16.79
j3  0      4.21    0      0      0       0       0
j4  6.17    0      0      0      0       0       0
j5  0      0      0      15.51   9.23     0       0
j6  0      0      0      9.49    0       0       0
j7  6.17    0      0      0      0       0       0
j8  7.28    0      0      0      0       0       0
j9  4.95    0.56    6.72    6.36    3.62     13.33    6.93;
table ca2(j,i)
    i1     i2     i3     i4     i5      i6      i7
j1  14.77   0      0      16.07   0       0       0
j2  0      0      12.97   10.36   0       13.47    26.06
j3  0      12.12   0      0      0       0       0
j4  14.71   0      0      0      0       0       0
j5  0      0      0      30.02   31.32    0       0
j6  0      0      0      15.62   0       0       0
j7  13.53   0      0      0      0       0       0
j8  13.05   0      0      0      0       0       0
j9  14.52   11.98   18.08   15.57   14.28    37.44    14.40;
```

```
table ca3(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  43.25   0       0       32.57   0       0       0
j2  0       0       47.67   26.82   0       42.7    0
j3  0       44.87   0       0       0       0       0
j4  40.39   0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       28.02   0       0       0
j7  38.92   0       0       0       0       0       0
j8  42.75   0       0       0       0       0       0
j9  40.69   41.69   41.37   35.81   35.37   55.40   29.94;
table ca4(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  60.08   0       0       0       0       0       0
j2  0       0       74.15   0       0       63.05   0
j3  0       57.15   0       0       0       0       0
j4  60.74   0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       0       0       0       0
j7  51.78   0       0       0       0       0       0
j8  62.76   0       0       0       0       0       0
j9  55.95   57.15   51.71   52.54   0       0       0;
table ca5(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  92.94   0       0       0       0       0       0
j2  0       0       82.16   0       0       83.75   0
j3  0       97.51   0       0       0       0       0
j4  88.44   0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       0       0       0       0
j7  83.91   0       0       0       0       0       0
j8  92.58   0       0       0       0       0       0
j9  88.43   96.78   42.06   0       0       0       0;
table ca6(j,i)
    i1      i2      i3      i4      i5      i6      i7
j1  0       0       0       0       0       0       0
j2  0       0       0       0       0       0       0
j3  0       0       0       0       0       0       0
j4  0       0       0       0       0       0       0
j5  0       0       0       0       0       0       0
j6  0       0       0       0       0       0       0
j7  0       0       0       0       0       0       0
j8  0       0       0       0       0       0       0
j9  0       0       47.67   0       0       0       0;
```

```
parameter ca(j,i,l);
ca(j,i,'l1')=ca1(j,i)*1000;
ca(j,i,'l2')=ca2(j,i)*1000;
ca(j,i,'l3')=ca3(j,i)*1000;
ca(j,i,'l4')=ca4(j,i)*1000;
ca(j,i,'l5')=ca5(j,i)*1000;
ca(j,i,'l6')=ca6(j,i)*1000;

scalar multi / 1.05 /;

parameter caX(j,i,l);
caX(j,i,l)=ca(j,i,l);
caX(‘j4',i,l)=ca(‘j4',i,l) * multi;
*caX(‘j8',i,l)=ca(‘j8',i,l) * multi;

parameter demand(i)
        / i1    72.165
          i2    50.603
          i3    3.399
          i4    7.675
          i5    1.640
          i6    8.007
          i7    2.791 /;

scalar P0       reference price / 30000  /;
scalar elast    elasticity      / 0.1 /;

parameter b(i) intercept of demand function;
         b(i) = P0/(elast * demand(i));

parameter A(i) slope of demand function;
         A(i) = P0 + demand(i) * b(i);

*--------------------------------------------------------------------------------
*
*-------------------------------------------------------------------------------

Variables
q(j,i,l) amount of supply demand in node i
d(i) demand in node i
W    amount of economic welfare
W2   amount of economic welfare  (Real)
pr(j)  production at zone j
```

```
pr2(i,l) production at yone j to i
pri(i)  price at node i
prALL
prof(j)  profit of the generator
lf1(m) line m flows
pF
pG
pN
pBN
pB;

positive variables
q,d,prALL;

Equations
welfare
welfare2
Energy_balance
ptdf_eq(m)
ptdf_eq2(m)
setp(j,i,l)
quantity(j)
quantity2(i,l)
price(i)
profit(j)
profit2(j)
wholeEU
regF(F1)
regG(G1)
regN(N1)
regB(B1)
regBN(BN1)
pos_profit(i,j,l)
lflow(m)
;

welfare..          W =e= sum(i, a(i)*d(i) - (d(i)*d(i))*b(i)/2) - sum(i,sum(j,sum(l,ca(j,i,l)*q(j,i,l))));
Energy_balance..   sum(i,d(i)) =e= sum(l,sum(i,sum(j, q(j,i,l))));
lflow(m)..         lf1(m) =e= sum(i, gamma(m,i) * (d(i)-sum(l,sum(j,q(j,i,l)))));
ptdf_eq(m)..       lf1(m) =l= Capk(m);
ptdf_eq2(m)..      lf1(m) =g= -Capk(m);
setp(j,i,l)..      q(j,i,l) =l= capg(j,i,l);

quantity(j)..    pr(j) =e= sum(i,sum(l,q(j,i,l)));
```

```
quantity2(i,l)..  pr2(i,l) =e= sum(j,q(j,i,l));
price(i)..       pri(i) =e= a(i)-b(i) * d(i);
profit(j)..      prof(j) =e= sum(l, sum(i, (q(j,i,l) * (pri(i) - ca(j,i,l)))));
pos_profit(i,j,l).. q(j,i,l) * (pri(i) - ca(j,i,l)) =g= 0;
wholeEU(i)..     prALL =e= pri(i);

regF(F1)..           pF =e= pri(F1);
regG(G1)..           pG =e= pri(G1);
regN(N1)..           pN =e= pri(N1);
regB(B1)..           pB =e= pri(B1);
regBN(BN1)..           pBN =e= pri(BN1);

welfare2..       W2 =e= sum(i, a(i)*d(i) - (d(i)*d(i))*b(i)/2) - sum(i,sum(j,sum(l,caX(j,i,l)*q(j,i,l))));
profit2(j)..     prof(j) =e= sum(l, sum(i, (q(j,i,l) * (pri(i) - ca(j,i,l)))));

Model nodal /welfare,Energy_balance,ptdf_eq,ptdf_eq2,setp,quantity,price,profit,lflow,quantity2
*regF
*regG
*regN
*regBN
wholeEU, pos_profit /;

Solve nodal using nlp maximizing W;

display W.l,A, b, pr.l,
pri.l,
prof.l,
q.l,
lf1.l,
pr2.l
;

loop(j,
loop(l,
loop(i,
put q.l(j,i,l);
);
put /;
);
put /;
);

Model nodal5P /
welfare2
```

```
Energy_balance
ptdf_eq
ptdf_eq2
setp
quantity
price
profit2
quantity2
lflow
wholeEU
*regF
*regG
*regN
*regB
*regBN

pos_profit
welfare
/;

Solve nodal5P using nlp maximizing W2;

display A, b, pr.l,
pri.l,
q.l,
lf1.l,
prof.l,
W.l,W2.l
pr2.l
;
loop(j,
loop(l,
loop(i,
put q.l(j,i,l);
);
put /;
);
put /;
);
```