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EMELIE-NET, a game theoretic approach including PTDF

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1. Abstract

In the last years there has been a strong development in the European markets towards liberalization. This development was a result of European legislation that is trying to force the electricity markets to converge to the ideal of the European domestic market.

Actually one of the most important obstacles against the fully homogenous electricity market is the high voltage network physical limitations factor.

The objective of the paper is to present the approach that explicitly integrate the problem of network constraints into the game competition model of European electric market, developed by Kemfert, Kalashnikov et al. (Berlin 2005, EMELIE Project).

For this purpose PTDF (Power Transfer Distribution Factors) were introduced into the model.

Through modification of other model components like the loss calculation the basis for a more general approach are made.

Further the EMELIE model was enlarged by some new (1st May 2004) member states of the European Union, namely Poland, Czech Republic and Slovakia.

Keywords: Game theory, PTDF, interconnected power system, electric market, load flow, congestions, competition.

2. Background and objective

In the last years there has been a strong development in the European markets towards liberalization. However this development did not come “sua sponte”, but was a result of European legislation that is trying to force the electricity markets to converge to the ideal of the European domestic market. In this context the EU-directive 2003/54/EG plays an important role.

This directive strives for liberalization enabling cross border trade and competition. Further the extension of the EU towards the East in May 2004 raised the number of countries affected by this legislation.

However there are still many obstacles that stand against the fully homogenous electricity market and one of the most important ones is the high voltage network physical limitations factor.

In fact, the interconnection of national electricity systems was initially designed to ensure their safe operation and in particular, to share and optimize the primary and secondary reserves required by safety standards. From this point of view, there is no doubting the success of the interconnection and harmonization achieved by the European electricity systems.

The electricity system deregulation process and the liberalization of the European electricity market are resulting in a strong growth of energy transits between national electricity transmission networks. In the last 30 years, the total volume of exchanges within the UCTE has increased by more than 500%, from approximately 50 TWh in 1975 to more than 260 TWh in 2003.

As a consequence the interconnection lines between the different member states are very often the decisive bottlenecks disturbing unlimited trade. In addition to that, within the countries of the European Union there are sometimes different homogenous zones with different marginal costs which are formed by the electricity infrastructure as shown in [5].

The liberalization of the European market made the academic community develop models dealing with the effects of liberalized electricity markets on prices, the consequences for congestion management and the impacts on environment via CO_2 and other emissions.

Ordered by the European Union, EMELIE [6] was developed as a market model taking into account several influence factors on electricity markets with a focus on emissions and trade.

EMELIE does not integrate the physical network model, but takes (indirectly) into account network constraints by attributing a trade capacity limits to each pair of countries. These trade capacity limits are defined kind that the whole of the physical limits of the network is respected. A calibration operation is needed for this purpose.

In order to simplify the calibration and to make it more coherent to the physical reality of the network, the authors have integrated into EMELIE model a network modeling module, based on the PTDF (**P**ower **T**ransfer **D**istribution **F**actor) approach. The new product was named EMELIE-NET.

This paper presents this product and treats the questions of the precision of the results in terms of their adequacy with the behavior of the real European electric system.

Some conclusions on the model improvement are drawn at the end of paper.

Approaches that include both, the physical network properties in form of an AC/DC load flow model or PTDF and the economic properties taking into account the strategic behavior of the companies are quite seldom. Most electricity market models that include the physical network properties in form of an AC/DC load flow model calculate electricity prices on marginal costs based merit order, the so called LMP approach. In this context the DC load flow model by Bill Hogan (1994) [9] provides a publicly available implementation in GAMS (= General Algebraic Modeling Language, a software tool for mathematical optimization problems). The impact of different kind of arbitrage in an electricity network was researched by Metzler, Hobbs and Pang (2003) [10]. In their paper the network is modeled via the PTDF approach, however their research focuses on the mathematical formulation of different market constellations and does not have any connection to a real existing electricity power system. Makoto Tanaka (2005) [11] examines regulatory incentive mechanisms for efficient investment in the transmission network. For modeling the electricity network he is also using PTDF values, however he is defining PTDF values in assuming a certain dependency between capacity and admittance and so in the PTDF approach in the above mentioned paper the PTDF values depend also on the capacity of a line. An analysis of the Croatian electricity network via the PTDF approach can be found in the paper of Dizdarevic, G. Majstrovic and M. Majstrovic [12].

3. The elements of EMELIE

EMELIE can be regarded as a game theoretic approach. The demand for electricity is considered to be isoelastic. The elasticity of demand is defined for base and peak load.

On the offer side there are the major electricity companies who are acting as players trying to maximize their profit. The smaller companies are summed up as fringe. The players can sell their electricity to neighboring countries, something the fringe cannot do.

Each player uses two production technologies and each technology is defined by its own cost structure and emission levels. Further each player has got a total capacity he can use for production.

A certain amount of energy is lost with every transaction.

The model calculates the results for the common economic market approaches, namely competition, Cournot-Nash equilibrium and Stackelberg equilibrium.

Further several scenarios taking into account different ways of emission treatment, like emission caps for each player, EU emission caps or emission trading can be used.

In its recent form according to [6] the model is limited to EU 8 namely, Belgium, Denmark, Finland, France, Germany, Holland, Norway and Sweden.

Further EMELIE includes transmission costs based on losses of Energy and shadow prices for binding interfaces who limit the trade between countries. Following a small description of the EMELIE approach taken from [6]:

“In a liberalized electricity market, firms maximize their profits by producing electricity with different kinds of technologies *i*, and by selling this electricity in the countries of a European market. In particular, producers distinguish between two separate markets based on the peak in electricity demand, namely peak hours and base hours.

The profits are the difference between the revenues from selling electricity and the costs of production. The prices of electricity differ across countries and load periods and in addition these prices might depend on the level of total electricity demand in a country during a particular load period. This dependency reflects particular strategic behavior of the electricity producers.

The firms base their decision on the amount of electricity produced given the load period, technology and market (*q, I, f, r, l*). The profit function for firm *f* is: $\Pi_f = \sum h_l \sum (p_{r,l}(S_{r,l}) s_{f,r,l}) - \sum h_l \sum (\sum c_{i,r} * q_{i,f,r,l})$ „.

l denotes the load type (base, peak), ***f*** is an element of the set of firms, ***r*** is an element of the set of regions, ***s*** stands for the supply of each firm, ***S*** represents the supply for each region and ***h*** represents the number of operating hours.

“The first term reflects the total amount of revenues from supplying electricity, while the second term summarizes the total amount of costs of electricity production. Note that the revenues depend on the amount of electricity supplied, and the costs depend on the amount of electricity produced by a given technology. The difference between the amount of electricity supplied or produced will be discussed below.

Firms maximize profits, although they cannot maximize profits unrestrictedly. There are three constraints that firms have to consider. First of all, the production of electricity is limited to the maximum operational electricity capacity owned by the firm. This does not rule out trade between countries, which is accompanied by the second restriction: the maximum capacity of the interconnections between countries. Finally, we include the possibility to impose emission restrictions on the production of electricity.” For a more detailed model specification and the documentation of the basic data please see [6]. The needed data for the EMELIE-NET model runs was also taken from the EMELIE original version if not disclaimed in another way.

4. EMELIE-NET

1.1 Elements

EMELIE-NET covers the countries of Nordel, namely Finland, Norway Sweden and at least partly Denmark. Further EMELIE-NET includes the western and central European countries of the UCTE – Network, namely Belgium, France, Germany, Holland, Czech Republic, Poland and Slovakia. Each country is considered to be a market with an isoelastic demand function of the form.

$D = D_0 * \left(\frac{p(S)}{P_0} \right)^{-e}$, where D_0 denotes the reference demand, P_0 the reference price and -e the elasticity of the demand. The production park and the production cost curves were taken from EMELIE [6], so for details about cost curves and the supply function [6] should be taken as reference.

1.2 The PTDF approach of EMELIE-NET

Today on the European HV meshed network we observe a very important difference between commercial and physical electric flows.

Figure 1 shows the flows for a France - Italy 1000 MW commercial transaction on the UCTE power grid. It is easy to see that a major part of the flows is outside the contractual path.

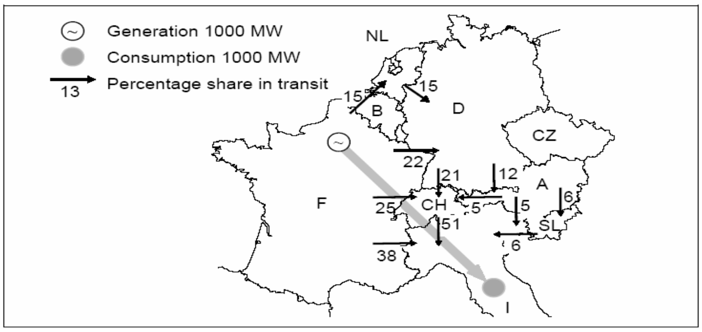

Figure 1: Power flow France-Italy transaction (Haubrich, Fritz, Study on cross border electricity transmission tariffs, Aachen 1999, p. 13)

Another relevant example can be regarded on the Figure 2. Here the power flows for a France Netherlands transaction were calculated. For this transaction even the majority of the power flows is outside the contract path.

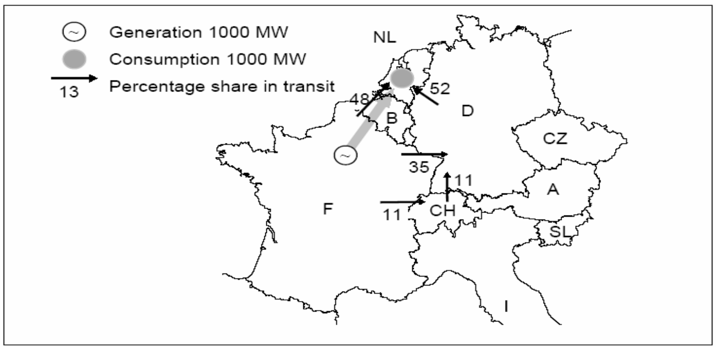

Figure 2: Power flow France Netherlands transaction (Haubrich, Fritz, Study on cross border electricity transmission tariffs, Aachen 1999, p. 13)

Figure 3 shows the power flow for a Czech Republic to Germany 100 MW commercial transaction. Even the Slovak Republic is affected by this transaction although lying in the opposite direction.

Figure 3: Power flow Czech Republic Germany transaction (UCTE, Newsgrid N. 11, Brussels, March 2005)

As result of this difference between the commercial and physical flows, some interfaces may turn out as bottlenecks limiting cross border trade without being directly touched by contractual transactions.

The only one accurate way to take this phenomenon into account is to associate to the European electrical market equilibrium model the load flow calculation module based on the Kirchhoff laws.

As example, on the Figure 4 is shown the power flows case resulting of commercial transaction from B to A. Assuming lines with identical parameters (impedance, resistance, and reactance), one third of the energy passes by C.

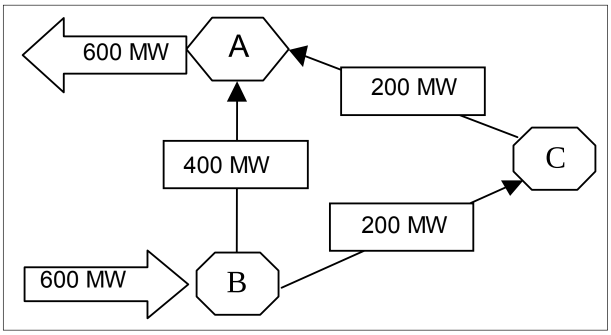

Figure 4: Power flow three line example

The PTDF (Power transfer distribution factor) approach consists in calculating the coefficients showing what part of energy is passing through which line/interface assuming a certain transaction. In the example of Figure 2 the PTDF values for an B to A transaction are 2/3 for line B to A, 1/3 for line C to A and 1/3 for line B to C.

In a very general approach one can say that the vector of the power flows corresponds to the product of the PTDF-Matrix multiplied with the vector of production/load.

$$(vector - of - powerflows) = [PTDF - Matrix] * (vector - of - production / withdrawls)$$

If all PTDF coefficients towards one bus (as called slack bus) are known, the other coefficients can be calculated.

Using that PTDF(A,B;B→C) = PTDF(A,C;B→C) - PTDF(B,C;B→C) helps to find some simplification for finding the power flows. C is chosen as the slack bus.

PF (A→B) = +1/3 (Prod(A)-Load(A)) - 1/3 (Prod(B)-Load(B))

$PF (A \rightarrow C) = +2/3 (Prod(A)-Load(A)) + 1/3 (Prod(B)-Load(B))$

$PF (B \rightarrow C) = +1/3 (Prod(A)-Load(A)) + 2/3 (Prod(B)-Load(B))$

In a meshed high voltage AC network these PTDF are constant, because they depend only on the physical network parameters (impedance, resistance, and reactance) and the network topology.

The knowledge of physical flows on the European network makes it possible to identify potential bottlenecks and consequently to limit the commercial transactions causing them.

However, the integration of the explicit load flow network model into the EMELIE market simulator meet several difficulties, in particular:

1. The European network data (network topology, lines and transformers impedance, resistance, and reactance) is not the open source information, its collection and validation seems delicate;
2. Knowing that the European meshed HV network contains more than 2500 nodes and more than 4000 lines, the integrating into an economic dispatch model based on the strategic behavior of the market participants, a full DC or AC load flow solver, can lead to a computing complexity that can be regarded as critical with actually available information and computation equipment.

In order to avoid these problems, a following simplifying approach was taken in EMELIE-NET model:

1. Each country taken into account in the model is represented with only one node;
2. The connections between nodes reflect the existing interfaces between countries;
3. The PTDF values for chosen interface could be considered as sum of the PTDF of lines forming this interface. It is called “zonal PTDF”.

Contrary to the nodal PTDF, which are constant, the zonal PTDF vary according to the operating point. Consequently for the different time points, the values of the zonal PTDF could be different. It means that the zonal PTDF matrix must be calculated separately for each time point scenario.

The PTDF values used for the EMELIE-NET calculations were taken from literature [13], [7], [8]. Although the paper of Haubrich et al. [7] is not using the word PTDF, but it exactly shows examples of PTDF calculations, how they are defined here.

As the full zonal PTDF matrix used by EMELIE-NET is too large to be put into this paper, below are shown only the most “important” interface PTDF values used in developing of EMELIE-NET model:

Switzerland - Germany	**Transactions from Germany to =>**				
	=> Austria	**=> Belgium**	**=> Switzerland**	**=> France**	**=> Netherlands**
Austria - Switzerland	-0.05	0.05	0.2	0.05	0.05
Austria - Czech Republic	-0.4	0	-0.1	-0.05	0
Austria - Germany	-0.3	0	-0.05	-0.05	0
Austria - Hungary	-0.25	0	-0.05	-0.05	0
Austria - Slovenia	0	0	0.05	0.05	0
Belgium - France	0	-0.3	0.1	0.25	-0.3
Belgium - Netherlands	0	-0.7	-0.1	-0.25	0.3
Switzerland - Germany	-0.05	-0.05	-0.5	-0.2	-0.05
Switzerland - France	0	0.1	-0.2	0.2	0.05
Czech Republic - Germany	-0.6	-0.05	-0.15	-0.1	-0.05
Czech Republic - Poland	0	0	0	0	0
Czech Republic - Slovakia	0.2	0	0.05	0.05	0
Germany - France	0	0.15	0.15	0.45	0.15
Germany - Netherlands	0	0.7	0.1	0.25	0.7
Hungary - Slovakia	-0.2	0	-0.05	-0.05	0
Poland - Slovakia	0.05	0	0	0	0

Table 1: Selected PTDF of European electric system used in developing of EMELIE-NET model

Let’s however notate, that as not all European countries are represented in actual version of EMELIE-NET model (in particular Switzerland, Italy, Austria, Slovenia, Spain and Portugal are not yet integrated in EMELIE-NET), the direct use of these PTDF values couldn't be realized.

Thus, a re-calculation of PTDF in order to take into account the whole European interfaces power flows is needed. This re-calculation leads to the losses in precision of the model, which makes it difficult, at the current stage, to engage on quantitative results of simulation and, in particular, on the values of the wholesale prices of electricity on the European electric markets.

The full-scaled zonal PTDF approach, taking into account the whole European interconnected system, is quite restricted concerning its accuracy, but has also got some obvious limitations which are visualized in Figure 5. Although several suppliers have contract with customers in the same zone (zone A), the physical power flow resulting of that contract crosses interfaces outside the contract path. In the UCTE network there are power flows across interfaces even if no cross border transaction takes place. Till now the zonal PTDF approach presented here does not address this problem.

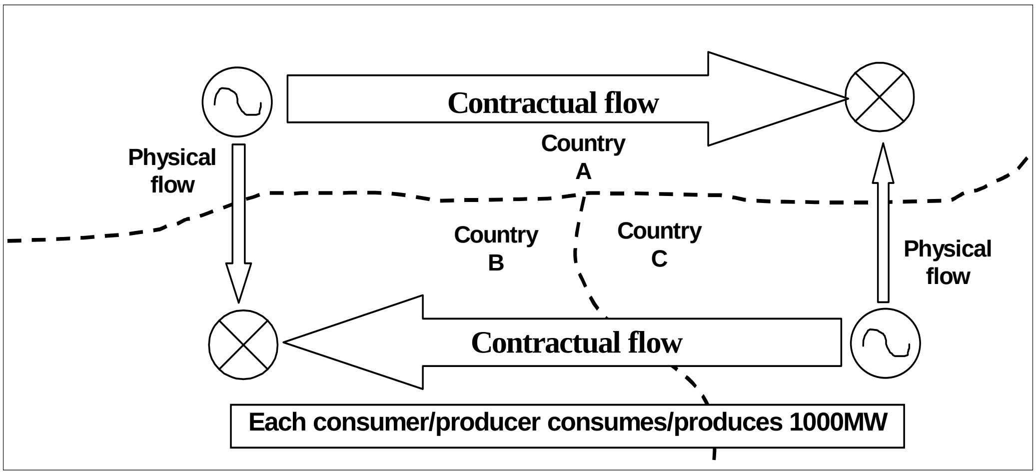

Figure 5: Inaccuracy of zonal PTDF

A further inaccuracy of this model roots in the fact that in a zonal approach every generator, who is located in one zone, is treated the same way. This assumption can be regarded as adequate for smaller countries or countries having a very homogenous network. For bigger countries within the UCTE zone, namely Germany and France this approximation can turn out to be quite rough. For example the influence of a power plant located in the south of France that is used to export electrical energy towards Italy will have less impact on France-Belgium interface besides the contract path than a power plant located in the north of France.

5. Simulation results and model assumptions

Before coming to the results some remarks about the data and the assumptions have to be made. The original EMELIE model contains some trade restrictions. Trade is only possible between two neighboring countries. This trade restriction was removed in EMELIE-NET. Only the competitive equilibrium and the Cournot model were calculated in order to reduce calculation time. Some features of the EMELIE original model like the calculation of the Stackelberg equilibrium were temporarily dropped. In the EMELIE-NET model all emission issues were also temporarily removed. As a first approach the PTDF-values were estimated if no public data was available. Small countries like Denmark were attributed the same PTDF-values like the next big neighbor country if no other values were found, in this case Germany. The countries of NORDEL (Finland, Norway, Sweden) are only taken into account as economic players. Their impact on the HV grid of the UCTE zone is the same as the entry country of the HVDC transmission line. This is due to the fact that these countries are linked to the UCTE region via HVDC lines which enable a quite good control over the power flow.

The maximal power flow between the interfaces is limited. The used capacity limits are based on the NTC values published by ETSO. For simplification it is assumed that capacity constraints within one region are not binding.

→To ←From	France	Holland	Czech Rep.	Poland	Slovakia
Belgium	2750	2400	0	0	0
Germany	5600	3300	700	2000	0
Czech Rep.	0	0	INF	1650	1800
Poland	0	0	1650	INF	750

Table 1: Capacity constraints, transmission capacities in MW

As example, the Table 3 shows the results for Belgium electricity prices and turn over delivered by the EMELIE-Net model.

Prices (Euro/MWh)		Electricity turn over (TWh)	
Competition	Cournot	Competition	Cournot
39,65	53,48	79,19	74,25

Table 3: selected results of EMELIE-NET (Belgium)

As it was already said, at the current stage, the EMELIE-NET model is not sharp enough to be used as a market prevision tool. However, the prices calculated by EMELIE-NET for the Belgian market correspond rather well with the statistics of market APX (as example, see figure 6 which shows the prices SPOT on APX for the 24 of September 2005).

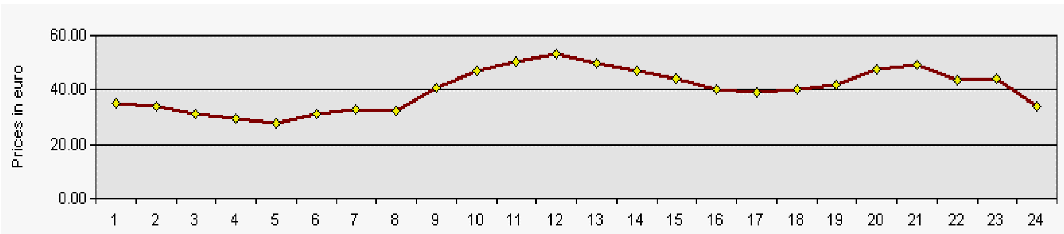

Figure 6: Spot prices on APX market for 24 /09/2005 (APX)

Table 4 shows the major exchange relations between UCTE countries according to the competition scenario. Some tendencies seem to be realistic. For example it is known for Poland that during base load periods Polish spot prices are higher than German spot prices, so Poland may import electricity from Germany and during peak load periods Poland is exporting electricity into Germany. This scheme is already indicated by EMELIE-NET even though the input data is not very precise.

From	To	Load type	Exchange in MW
France	Belgium	Base	400
Belgium	France	Peak	2417
France	Germany	Base	1895
Germany	France	Peak	980
Germany	Poland	Base	286

From	To	Load type	Exchange in MW
Poland	Germany	Peak	864
Czech Republic	Slovakia	Base	1297
Slovakia	Czech Republic	Peak	461

Table 4: exchanges according to EMELIE-NET

6. Future development

Last but not least a small outlook what further improvements for the EMELIE-NET model can be regarded as useful for the future is given in the following part.

For the moment losses are not regarded because for the reconstruction of the load flows they can only play a minor role. Concerning the transmission costs they are quite important. However it is difficult to treat losses because there is a different way to externalize the costs in the different countries. For example the losses are bought by the TSO and paid with the network access fee. In Germany this fee is paid to 100 % by the consumer. In Sweden both the generator and the consumer have to pay a network access fee in the ratio of 30/70. Further in the EMELIE model the losses are calculated transaction based and can be considered as an amount of energy that is lost for every transaction. In reality this simplification can be considered as quite rough. In general it is necessary to have knowledge of the physical power flows in order to be able to calculate losses.

Further the choice of countries should be extended. It is very difficult to create a realistic model of the UCTE network without taking into account Switzerland. Switzerland can be regarded as an important transit country for energy flows, because of its central position. The terrain of Switzerland is covered with mountains and as a consequence it can be assumed to be quite expensive to enforce the grid in Switzerland. Further the interfaces of the neighboring countries normally have not a lot of excess capacity. Since all these reasons the electricity grid in this region turns out to be a potential bottleneck for many transactions. It is only consequent to take this part of the UCTE network into account in order to gain accuracy for the whole model. In this context we must also mention the importance of Italy in European market. Italy is the main European electricity importing country. Because of its geographic position, transactions to Italy charge the sensitive

Swiss interface lines. Further Italy offers one of the most attractive export options in Europe for electricity generation companies.

7. Conclusions

The process of the European Community enlargement contributes inter alia to the harmonization of the electric legislations of European countries as regards trade of electricity. The deregulation of the energy sector accelerates, the role of the European electric market becomes increasingly important.

Thus, the analysis of evolution of competition on this market and its impact on the prices of electricity became a key element of debates on the future design of the European electric market. In this context, the EMELIE – Net project contributes to this spot, while launching a "network" dimension integration in the economic model of the European electric system.

Today model EMELIE-NET is under construction. The qualitative results (and in particular with regard to the exchanges between the countries) are encouraging.

It is however not yet possible to engage on the computation results of the wholesale prices of electricity.

The most important future developments of the EMELIE-NET, leading to make it fully operational tool, are:

- Integrating all UCTE countries electric systems into model;
- Introducing the high voltage network losses into the prices calculation module;
- To update the data on the producers and the consumers in all the countries present in the model.

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