Antonis Papaemmanouil[1], Evdokia Kaffe[1], Göran Andersson[1]

GENERATION PROFITS IN MULTI-AREA POWER MARKETS CONSIDERING GREEN CERTIFICATES

[1]Power Systems Laboratory, ETH Zurich, Switzerland, +41 44 632 69 04
ekaffe@student.ethz.ch
{papaemmanouil,andersson}@eeh.ee.ethz.ch

Overview

The effort to integrate the national and regional power markets of Europe, i.e. NordPool, APX, EEX, EXAA, OMEL etc., into one unified European power market has intensified lately. However, regulation and congestion treatment differences inside Europe combined with constantly increasing electricity demand make it more difficult to achieve such an integrated power market. Besides, the different applied market structures Europe-wide create more complicated operating conditions and thus the profitability of generation investments and their impact on transmission network and vice-versa, becomes a quite tricky task. Towards the next generation of the European power system additional transmission and production capacity is needed in order to cover the increasing demand and the environmental requirements of a sustainable development. This reinforcement can either be profitable for the generation companies, for the consumers, for the transmission grid increasing its operational efficiency or to some extend after strong coordination for all market participants [1]. This paper deals with the generation profits of companies that own production capacity in different areas, when constraints for green certificates and for the transmission network are applied. A multi-area decomposition methodology has been used for the power exchange representation and has been compared with a more centralized market structure like the nodal pricing scheme. The results has shown that nodal pricing is more cost efficient leading to lower total production costs in case of congestion, and thus to lower congestion costs. The green certificates market introduced here is based on nodal pricing approach and provides locational price signals in the short-run as well as optimal capacity of new green investments on each node in order to cover the demand for green certificates.

Introduction

Liberalization is one important step in the transition from national power markets towards a unified European market. Market liberalization includes opening of both the production and consumption markets. This way, a producer can choose to invest in any European country and the consumer can choose to buy the power needed by any energy carrier available. The ultimate goal is, under strong coordination of all market participants, profit maximization for all generation companies and customers. At the same time, satisfaction of reliability and quality standards by the transmission grid is required.

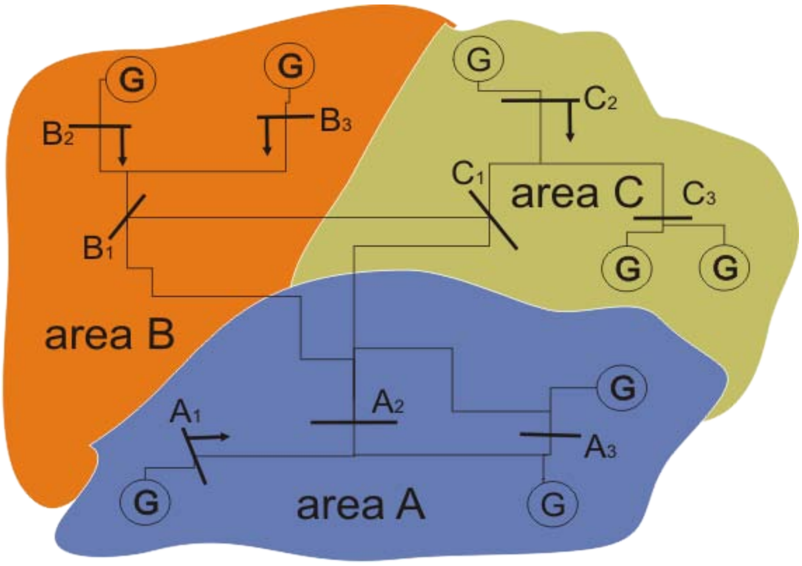


Figure 1: A simplified model of a liberalized power system. Three areas interconnected system with loads, generators and transmission lines. Production companies are allowed to own power plants in any area in order to maximize their profits.

Such a liberalized power system could have the form presented in Fig. 1. The system consists of areas with nodes where both generators and loads exist. Generating companies are allowed to operate in all areas and consumers have the option to choose who they get their power from according to the monitored in-feed tariffs.

The electric power system obeys physical laws. Therefore, when an alteration takes place in any part of the system, it spreads instantaneously to other parts of the interconnected network causing unwanted results as the load conditions are differentiated. Power flows can only be partially controlled. This can be done either by using devices such as phase shifting transformers and HVDC lines to exercise limited control or by restructuring the system to introduce competition. Due to the high cost of the above mentioned devices, the latter solution is preferred [2]. Restructuring mainly includes introduction of competition in the generation. This is mainly done by liberalizing the market. This way, efficiency is improved and sometimes, for fast developing countries, private investments are attracted.

Until restructuring, the transmission system functions were mainly to link generation to load and enhance system reliability. With the introduction of competition, many generators can compete in an aggregated market to satisfy the total system needs. On the other hand, if transmission is not adequate, bottlenecks could be formed giving market power to certain generators in the network. Thus, transmission system should also try to mitigate this market power.

Most electricity markets today can be characterized as “Managed Spot Markets” [3] because a certain price is determined at each spot but the bids and offers resulting in this price are not made through bilateral agreements but are managed by the system operators (SOs). ENTSO-E, the association of European Transmission System

Operators (TSOs) consists of 42 TSOs from 34 countries. In order to deal with cross-border congestions more effectively, ENTSO-E recommends that TSOs of neighboring areas coordinate their activities.

Transmission System Operators have three main missions [4]. The first is to manage electricity flow externalities in the short run. Such externalities are congestion on the grid lines or power losses across the transmission system. The second one is to contribute in the grid development in the long run and the third is to coordinate with neighboring TSOs in order to avoid border effects as it was mentioned before. According to the mission they aim to fulfill, a different management behavior is chosen by the TSO. This behavior is expressed by the pricing system used in the grid and by how externalities are internalized in this pricing system. Therefore, the ideal TSO is defined as the optimal combination of choices for each mission to be fulfilled.

1. Market Structures

As mentioned above, the goal of the TSO in the short term is to manage the externalities coming from congestion on the grid or power losses. In order to internalize network externalities, several pricing options exist. In this paper, two different market structures are studied and the results of each one in generator profits and carbon emissions are examined while the transmission network capacity is taken into account. The first, nodal pricing, is a price deterministic method where an equilibrium point and clearing price is calculated for each node of the system [5]. A node represents a specific location in the transmission grid where power is provided by the generators and withdrawn by loads. The objective is the maximization of social welfare. In case of no congestion in the transmission grid the same nodal price appears at all nodes. The second market structure studied is the power exchange. In this case, one common price for electricity is calculated, not for each node, but for each area. Power trading between areas is allowed and production companies may own a production capacity in any area, e.g. coal, wind, hydro, gas and nuclear.

1.1. Nodal pricing:

An electricity price at each node of the grid is assigned. This price shows in which node is more profitable to consume an additional MWh. Grid capacity, demand coverage and other possible externalities are considered during price determination. The externalities of the grid are considered as constraints in the market clearing. When no congestion in the transmission network occurs, one single nodal price all over the system appears. The minimization problem is a non-linear constrained problem, referring to the minimization of total production cost. In our case linear production costs for each one of the generators (1…n) have been used:

$$\underset{x}{\text{minimize}} \; f\left(x\right), \quad f=\sum_{i=1}^{n} a_i \cdot \text{supply}_i + \frac{1}{2}\cdot b_i \cdot \text{supply}_i^2$$

s.t.

1. Transmission limits inequalities

$|\text{Power\_flow}_{ij}| < \text{TCL}_{ij}$, TCL : transmission capacity limit

2. Maximum/minimum production limits for each node

$0 < \text{Supply}_i < P_{max}$, Pmax: maximum generated power

3. Power balance equations for each node

$$\sum \text{nodal\_injections} = 0,$$

where nodal_injections is the positive injected power from generators connected on the node, plus the negative injected power of the loads, plus the power that flows in/out of the node from other nodes.

The final solution provides the dispatch of each power plant and the equilibrium nodal prices of the power market for specific demand. This approach is called DC optimal power flow [6].

1.2. Power exchange

Through the power exchange market structure the trading becomes easier and market information and competition is promoted [7]. Other advantages of Power Exchange are a neutral marketplace, a neutral price reference, easy access, low transaction costs, a safe counterpart, and clearing and settlement service. Moreover, spot market prices are an important reference both for over-the-counter (bilateral) trading, and for the trading of forward, future and option contracts.

Several trading systems, market types and pricing rules can be applied differentiating the various Power Exchanges across Europe. Considering the trading system, in our case the market clearing price is defined through continuous trading, a much simpler option compared to auction trading system. Furthermore, a real-time market is assumed for simplicity.

The modeling of power exchange has been based on lagrangian decomposition (LR) proposed in [8], [9], [10]. The LR is a common method of analysing multi-area power systems as described in [11], where a system of multi-energy carries with 3 areas is described. The co-ordination of gas, heat and power using aggregated characteristics of each area is in focus. In our case, only electricity is considered. The network has been divided in three areas with aggregated supply and demand curves. The producers are price takers and the most expensive accepted bid defines the area price. At the same time, power trading between areas is allowed through interconnection lines. The transmission grid capability within each area has been neglected.

More specifically, the Optimality Condition Decomposition (OCD) technique, being used here, can be interpreted as a particular implementation of the Lagrange Relaxation (LR) procedure [12].

A simplified problem with two variables illustrating the OCD technique is presented here:

$$\underset{x_1,x_2}{\text{minimize}}\ f(x_1,x_2)$$

s.t.

$$h_1(x_1,x_2)=0$$

$$h_2(x_1,x_2)=0$$

$$c_j(x_j)=0; \qquad j=1,2$$

Where the constraints $h_1(x_1,x_2)$ and $h_2(x_1,x_2)$ are complicating constraints, i.e. constraints that if relaxed, the problem becomes drastically simplified.

The basic LR procedure applied to this problem considers the new problem:

$$\underset{x_1,x_2}{\text{minimize}}\ f(x_1,x_2)+\overline{\lambda}_1^T\cdot h_1(x_1,x_2)+\overline{\lambda}_2^T\cdot h_2(x_1,x_2)$$

s.t.

$$c_j(x_j)=0; \qquad j=1,2$$

Defined in terms of multiplier estimates $\overline{\lambda}_1$ and $\overline{\lambda}_2$. The initialization of $\overline{x}_1$, $\overline{x}_2$ and $\overline{\lambda}$ helps to formulate the sub-problems, keeping one of the two variables fixed:

$$\underset{x_1}{\text{minimize}}\ f(x_1,\overline{x}_2)+\overline{\lambda}_1^T\cdot h_1(x_1,\overline{x}_2)$$

s.t.

$$c_1(x_1)=0$$

and

$$\underset{x_2}{\text{minimize}}\ f(\overline{x}_1,x_2)+\overline{\lambda}_2^T\cdot h_2(\overline{x}_1,x_2)$$

Subject to

$$c_2(x_2)=0$$

In order to obtain the final solution an iterative process updates the values for $\overline{\lambda}_2$, $\overline{\lambda}_1$ and $\overline{x}$. The process stops when the optimality criterion is satisfied.

In our case, the goal is to maximize the social welfare. This can be done by minimizing the cost, since the demand is assumed to remain constant. The complicating equalities and inequalities are included in the optimization function:

$$f_{area\ \mathrm{i}} = a \cdot \mathrm{supply}_{\mathrm{i}} + \frac{1}{2} \cdot b \cdot \mathrm{supply}_{\mathrm{i}}^{2} - \sum_{\substack{area\ \mathrm{j} \\ \mathrm{j} \neq i}}^{k} \left[\lambda_j \cdot \left(P_j - L_j - E_j \right) \right] -$$

$$- \sum_{\substack{area\ \mathrm{j} \\ \mathrm{j} \neq i}}^{k} \left[m_j \cdot \left(line_{jj'}\_capacity - abs(power\_flow_{jj'}) \right) \right], k = \#areas$$

s.t.

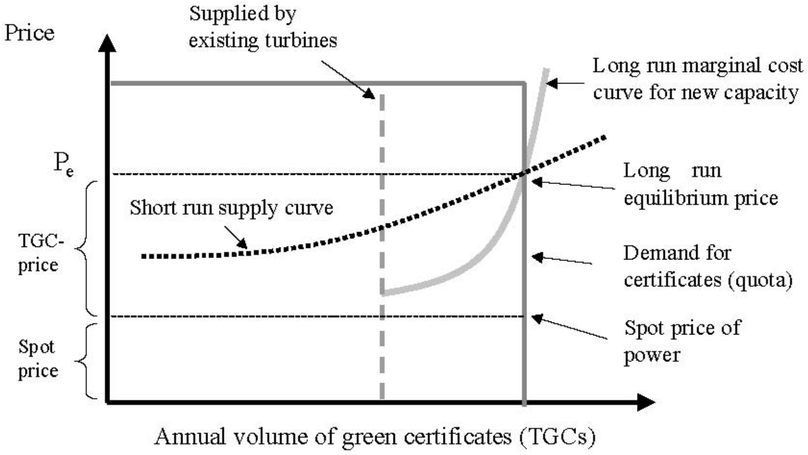
1. Transmission limits inequalities for all connected lines to area i
2. Maximum/minimum production limits for area i
3. Power balance equation for area i

In the power exchange, participate the same generators as in nodal market structure, however aggregated demand applies.

1.3. Green certificates

Green certificates (GCs) are financial assets provided to companies of renewable production in order to promote green investments. The investment risk is minimized through long-term contracts with the consumers. Price signals are provided based on marginal production prices for future green technologies, clearing a market of supply and demand for green certificates [13]. In this market only renewable technologies participate, that are initially certified. Usually wind, solar, hydro and biomass are the major participants, however in this paper only wind and solar power is considered as provider of green certificates. When Morthorst [14] proposed a country-wise approach of an international green certificates market, the location in the network and the renewable technology was not specified. The system was divided in countries with more aggregated characteristics.

Figure 2 Price determination and the relation between long and short run in a green certificate market [14]



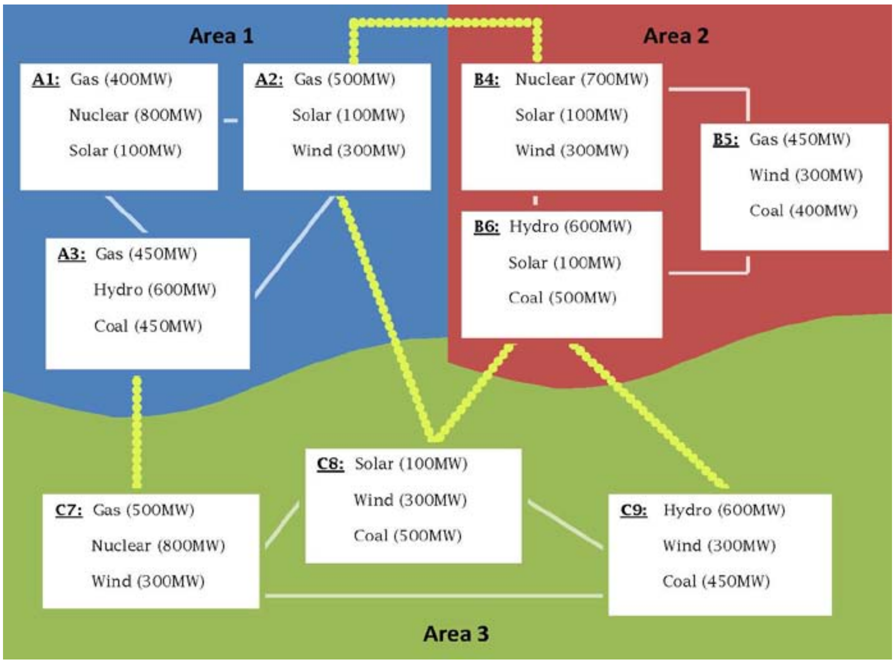
In a nodal market environment, borders do not exist and the idea of locational green certificates, presented here, is easily implemented. The assumptions in the implementation of the GCs market are noticed below:

- Market participants are only producers of wind and solar power.
- The supply of GCs is based on the marginal production cost curve of new solar or wind power on the already existing site for the three areas.
- Demand of GCs from consumers (long-term contracts, inelastic).
- Market equilibrium targeting to minimization of investment costs, intersection of supply and demand of GCs. Trading between nodes is allowed.
- The GCs price is equal to the marginal production cost for new investments minus the spot sprice. The GCs prices are influenced in the long-term from spot price fluctuations because of discontinuations of wind or solar power availability, however in the short-term congestions in the transmission network can send different price signals for GCs in different locations of the network.
- Power market and GCs market are two parallel markets and the optimization proceeds at the same time. The production costs of electricity (PCel) and the investment costs of renewables (ICren) are minimized. The only additional constraint in the GCs market is that the supply of GCs has to cover the demand of GCs. As the GC market is just a financial market the spot price is not influenced from the GC price.

2. Studied model

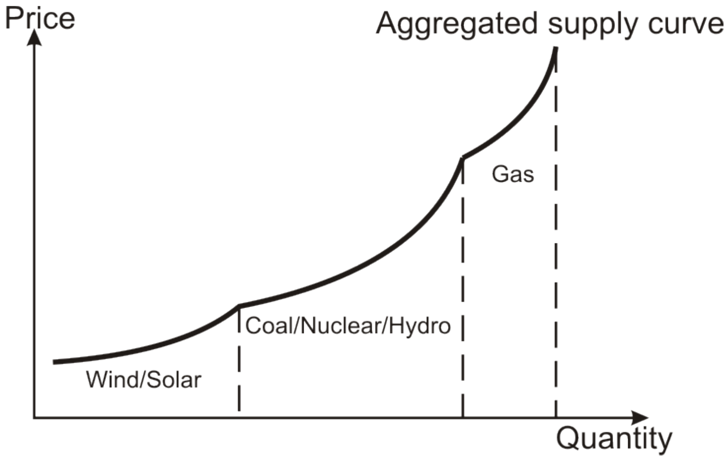
The network under study consists of three hypothetical areas, Fig.3. Each area includes three nodes and each node includes three power plants of different types. In total six types of production are considered, i.e. gas, coal, nuclear, wind, solar and hydro.

Figure 3 The model



Production companies are allowed to own power plants in any area in order to build a portfolio mix and maximize their profits. Apart from the companies production mix, some general assumptions apply: solar power is the cheapest in area 1, wind power is the cheapest in area 2 and in area 3 are both equal expensive. For hydro power however the same costs in all areas appear. The cost curves of solar and wind power are such that they always participate in the price determination mechanism, Fig. 2. The initial percentage of demand covered by solar and wind power is equal to 40%.

Figure 4 Representation of production costs ranking



The areas are interconnected and transmission capability limits have been taken into account.

2.1. Congestion cases:

Case 1: No congestion. The power flow in all lines is below the transmission limits.

Case 2: Congestion inside an area. The transmission limit of the line connecting the nodes A1 – A2 of area 1 has been reached. This line was chosen because of the largest nodal price differences.

Case 3: Congestion between two areas. The transmission limit of the line connecting A3 and C1 has been reached.

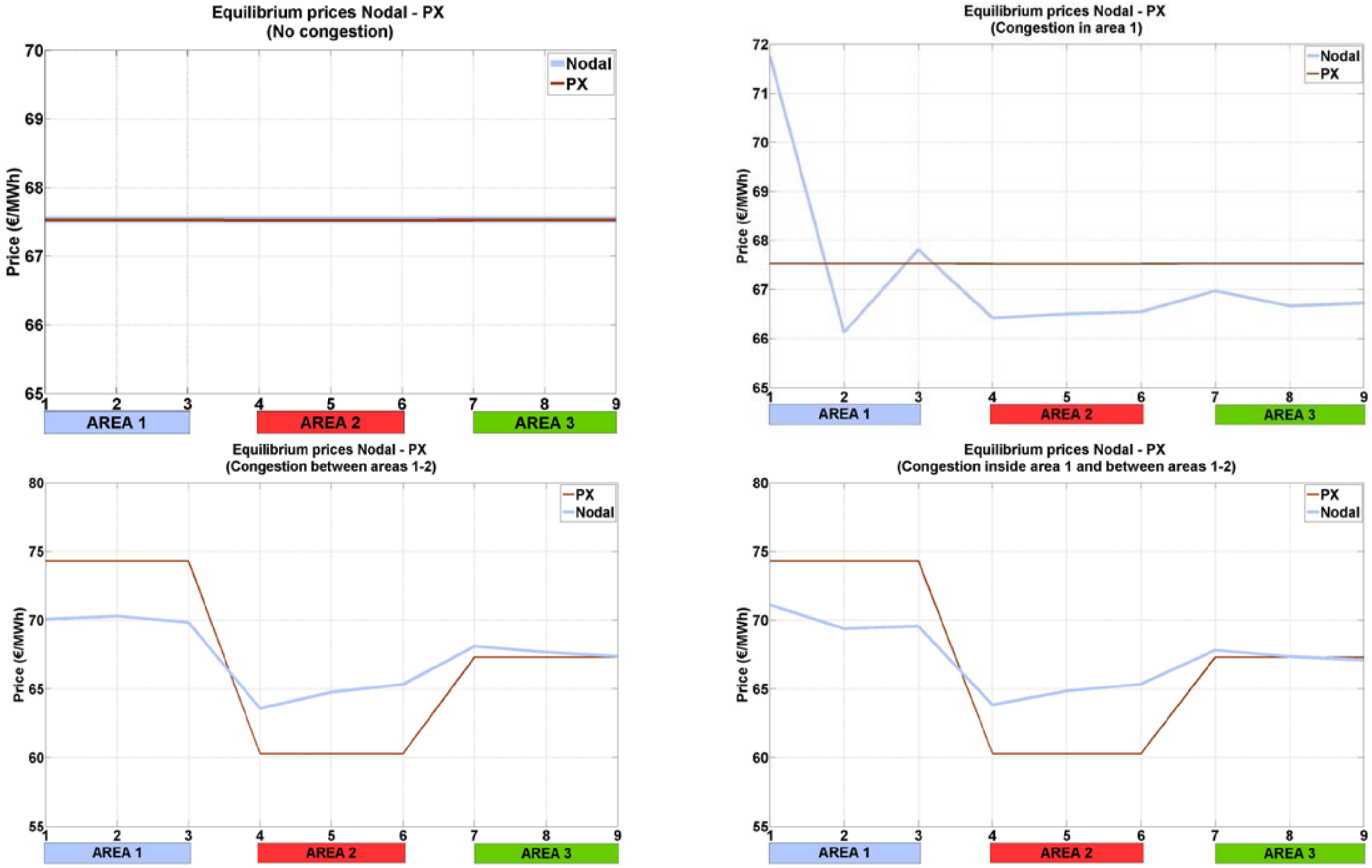
Case 4: Congestion both inside and between areas. Two lines are congested; one connecting the nodes A3 – C1 and one connecting the nodes A1 – A2.

3. Results

In this section the two market structures (nodal pricing, power exchange) are compared, for the different cases of transmission network availability and the results of the GCs market are presented. The reason of comparison is to understand how the two market structures behave in case of congestion and to examine whether there are any profit differences for some of the three companies.

In Fig. 5 the differences in nodal prices are shown. Without any congestion one price appears in the whole system, which is identical for both market structures. The power exchange (PX) does not react in congestions inside areas, thus although there is a quite large price difference inside area 1, the PX does not change its price. In the other case of congestion between the two areas 1-3 the PX gives different prices for the 3 areas which are different from the prices of nodal approach. It is obvious that the nodal structure reacts smoother than the PX, and the price differences between areas are smaller. This result shows that nodal pricing is more efficient regarding the coordination of the participants, as the available production can easily be better dispatched. Smaller price differences means also smaller congestion costs for the same amount of power between the same nodes.

Figure 5 Nodal pricing and Power exchange (PX) comparison for several congestion cases of the transmission network



The table 1 below describes the generation profits of each generation type and the simulation time in MATLAB. The generation profits difference between the two market structure seems to be negligible, regardless the nodal price differences. Probably the price difference is not big enough in order to influence the profits. However, major production profits deviations appear in dispatchable power, i.e. gas.
Regarding the simulation time, the decomposition technique applied here is by far slower than the DC OPF for nodal pricing. This happens because of the iterations needed in order to find the equilibrium price between areas. The market information is distributed in a sequential way that makes the whole process very slow. Thus, coordination in nodal approach is faster and more efficient.

Table 1 Generation profits in several congestion cases

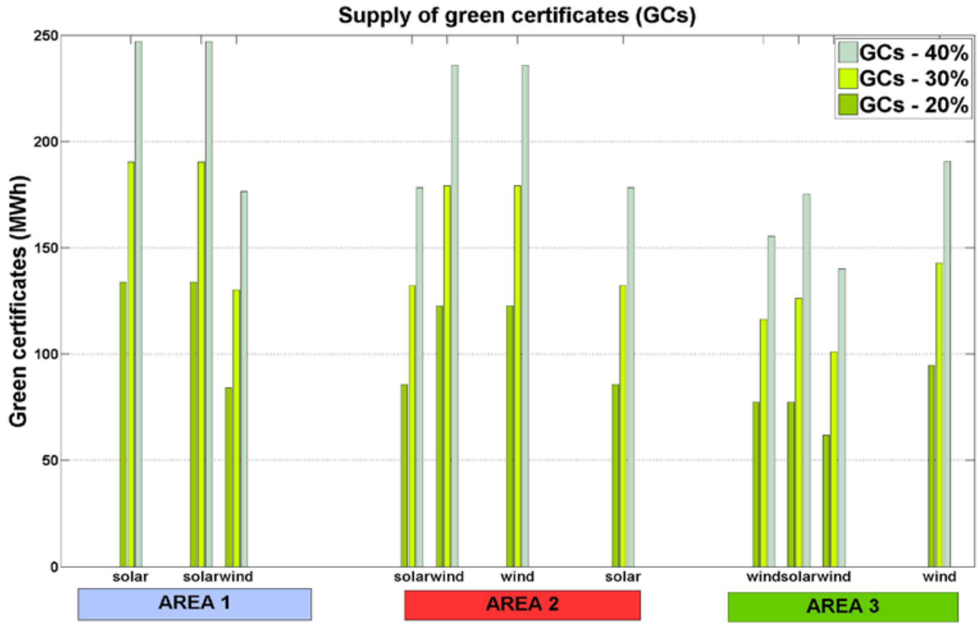
	No congestion		Congestion area 1		Congestion between areas 1-2		Congestion inside area 1 & between areas 1-2	
Profits (€/MWh*10^3)								
	PX	Nodal	PX	Nodal	PX	Nodal	PX	Nodal
Solar	25	25	25	25	24.9	25	24.9	25
Wind	71.1	71.1	71.1	69.3	68.6	70	68.6	69.6
Hydro	30.5	30.5	30.5	30	30.5	30.5	30.5	30.3
Coal	23.77	23.77	23.77	23.25	22.7	23.37	22.7	23.26
Nuclear	31.15	31.16	31.15	32.03	31.19	30.94	31.19	31.28
Gas	13.33	13.33	13.33	13.52	14.95	13.96	14.95	13.92
Time (s)	3.68	1.39	3.76	1.36	2.48	1.58	2.68	1.38

Summarizing the advantages of nodal pricing against the power exchange using the LR decomposition technique:

- Efficient pricing, better use of available capacity
- Faster coordination
- Lower congestion costs

The aforementioned results explain the reason why the nodal approach has been also used for the green certificates market. It gives to the decision maker locational information of the optimal amount of renewable power that can be dispatched from a certain point in the network, regarding investment costs. Based on marginal production cost curves for new solar and wind power, where the already existing power plants are, the investor knows how much new green power could be installed for covering a specific demand. In Fig. 6 below the green certificates supply for three levels of additional power from renewables (20%, 30%, 40%) is presented. Therefore after the installation of the additional demanded green power, the total amount of demand that will be covered from solar and wind power will be 60%, 70%, 80% respectively.

Figure 6 Amount of green power that should be installed in order to cover different levels of green power demand



In Fig. 6 it is obvious that it is more profitable to install wind power in nodes 1, 2 of area 2 and solar power in nodes 1, 2 of area 1. The third area is quite expensive for both production types, so less new green power will come from there.
In the long-run the green certificates are like contracts between the suppliers and the customers and so a fixed price for different demand levels is set. The GC prices and the profits for solar and wind power are presented in the table 2 below.

Table 2 Generation profits following the GC market

	Q = 20%	Q = 30%	Q = 40%
Solar	41	68.9	109.8
Wind	95.2	126.2	171.6
GC price	32.6	58.1	83.5

Nevertheless, a fixed price between suppliers and consumers would create some deficit for the suppliers in the short-run, when the transmission network is congested and the GC prices are higher. As long as the GC price depends on the spot market price, GC prices will be affected also from transmission network availability. Fig. 7 describes the different GC prices in the short-run on every node of the system for the aforementioned congestion cases.

Figure 7 Green certificate prices in the short-run

4. Conclusions

The advantages of a nodal pricing structure using a DC-OPF against a power exchange modeled with LR decomposition technique are presented. From the results derives that nodal pricing is very cost efficient, helps the coordination of the nodes and leads to lower congestion costs in case of limited network transmission availability. As environmental constraints become more and more part of the energy systems and the market structures are changing, the latter analysis can support decision makers in the planning of the future electricity system. Two power market structures are compared and based on the most profitable, i.e. nodal pricing, a locational green certificates market is introduced. This gives information on how much additional green power is needed on each node in order to cover a specific amount of power coming from renewables. In the long-run the GC prices could be used for fixed contracts between producers and consumers, but in the short-run this could create financial losses for the suppliers.

5. References

[1] Marinescu, B., Coulondre, J-M., Tsamasphyrou, P., Bourmaud, J-Y. (2005). *Improving TSO's coordination for cross-border redispatch: a discussion of possible approaches in the European context.* 2nd CIGRE/IEEE PES International Symposium Congestion Management in a Market Environment, San Antonio, October 5–7.

[2] Wu, F. F., Zheng, F. L., & Wen, F. S. (2006). *Transmission investment and expansion planning in a restructured electricity market. Science Direct, Energy 31* , 954-966.

[3] Kirschen, D., & Strbac, G. (2004). *Fundamentals of Power System Economics.* John Wiley & Sons, Ltd.

[4] Rious, V., Glachant, J.-M., Yannick, P., & Dessante, P. (2008). *The diversity of design of TSOs. Energy Policy 36* , 3323-3332.

[5] Quelhas A., Gil E., McCalley J. (2006). *Nodal prices in an integrated energy system*. International Journal of Critical Infrastructures, Vol. 2, No.1 pp. 50 - 69.

[6] D. Sun (1996). *Application of the OPF in deregulated electricity market.* IEEE/PES Winter Meeting, January.

[7] Madlener, R., & Kaufmann, M. (2002). *Power exchange spot market trading in Europe: theoretical considerations and empirical evidence*. OSCOGEN.

[8] Conejo J. A., Aguado A. J. (1998). *Multi-area coordinated decentralized DC optimal power flow*. IEEE Trans. Power Syst., vol. 13, no. 4, pp. 1272–1278.

[9] Keyan L., Wanxing S., Yun-hua Li (2005). *Research on Parallel Algorithm of DC Optimal Power Flow in Large Interconnection Power Grids*. In: ICEMS 2005, Vol. 2, pp. 1031 – 1036.

[10] Conejo J. A., Nogales J. F., Prieto J. F. (2002). *A decomposition procedure based on approximate Newton directions*. Math. Program., Ser. A 93: 495–515.

[11] Michèle Arnold and Göran Andersson (2008). *Decomposed Electricity and Natural Gas Optimal Power Flow*. 16th Power Systems Computation Conference, Glasgow, Scotland.

[12] Conejo, A. J., Castillo, E., Minguez, R., & Garcia-Bertrand, R. (2006). *Decomposition Techniques in Mathematical Programming, Engineering and Science Applications.* Springer.

[13] Jensen, S.G., Skytte, K.(2002). *Interactions between the power and green certificate markets.* Energy Policy 30, 425–435

[14] P.E. Morthorst (2002). *A green certificate market combined with a liberalised power market.* Energy Policy 31, 1393–1402.