Multi-area electricity market equilibrium model and its application to the European case: an efficient approach to study non-perfect competition

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***Abstract*—This paper presents an efficient approach for computing medium-term market equilibrium models under non-perfect competition, with a focus on multi-area systems, with multiple market splitting options. In accordance to the new policies and regulations aimed at creation of the Internal Electricity Market (IEM), Europe is evolving towards an integration of the electricity markets under a unified framework. Integrating the electricity markets already existing in the European countries represents a great challenge, since multiple agents' strategic behaviors may appear depending on the state of the interconnections. When modeling this effect, the aim is to characterize each strategy by means of a conjectured price response, as a function of the states of the network. The methodology introduced in this paper reduces the possible network configurations thereby making the problem computationally tractable. Finally, this methodology has been applied to a two-year planning model for a set of nine European countries.**

***Index Terms*-- Conjectural Variations, European Internal Electricity Market, Market Equilibrium, Optimization Models.**

I. INTRODUCTION

In the last decades, the energy sector has undergone a profound liberalization. Along with this process, electricity markets have progressively become the focus of interest in many studies and research. At the same time, in accordance to the new policies and regulations aimed at the creation of the Internal Electricity Market (IEM) [1], Europe is evolving towards an integration of the existing electricity markets under a unified framework. This new market structure is expected to enhance economic efficiency and reduce market concentration. The improvement of the security of supply and, as a consequence, the reduction of reserve capacity are the other top priorities [2–4]. However, all these benefits are possible to a great extent only with the coordination of the different regulators and market agents, with sufficient interconnection capacities as well as with a robust and effective procedure to clear congestions.

Furthermore, the electricity markets in Europe are arranged with a zonal-pricing design, thereby ignoring congestions within zones. Zonal-pricing markets (also referred to as area-pricing markets) establish different electricity prices for different areas of the system. These areas or zones are predefined a priori depending on the network characteristics in the system. At the same time, the electricity markets in Europe are consistently interconnected through transmission lines and economic mechanisms. Consequently, the electricity price is equal for all market agents in the same area and, should congestion in the interconnections be ignored, the price will be the same in the whole system.

As a result, market integration appears to be strongly influenced by cross-border exchanges. Hence, the importance of the interconnections in this integrated system constitutes a principal area of research. Network constraints incorporate additional issues to the system operation. Limitations of transmission capacity may provoke market segregation, which in turn may enable market participants to exercise regional market power. This decreases competition and increases electricity prices [5, 6]. The integration of the European market is eased with a market coupling mechanism. It manages interregional market interactions using the interconnection capacities between two neighboring areas in an efficient way.

In this situation, models that faithfully simulate the outcome of the electricity market are especially relevant for regulators and market participants, to ensure a correct planning and operation of the market.

Traditionally, one of the most widespread methods to analyze generators competition in electricity markets is based on finding the market equilibrium. This approach started off from the economic concept of Nash Equilibrium [7, 8], that marked the beginning of game theory. Equilibrium models in electricity markets define the equilibrium as a set of prices, power outputs, transmission line power flows and cleared demand which maximize each participant's benefit while clearing the market [9, 10]. Market equilibrium models allow for representing market behavior involving all the participants, and becomes the most suitable method for market power analysis, at least in the medium- to long-term time scope.

The literature has proven that a considerable effort has been made by researchers in studying market equilibrium models and their application to real power systems. An extensive classification of market equilibrium models and their applications can be found in [11, 12].

With regard to power system models that comprise several areas in particular, the literature is not that wide. For instance, both [13] and [14] propose a conjectured supply function (CSF) equilibrium model in an electricity market including network constraints. In [13], the author compares two different congestion mechanisms for clearing the market in cross-border transactions: market splitting and explicit auctions; analyzing the market power market participants can exercise in each situation. In [14], the analysis states that the conjectures of price response depend on the status of the networks, following a function of the congestion. However, the model is applied to a system with only two areas. The same areas are also considered in [15]: the work proposes a conjectural variation-based (CV) equilibrium model using Mixed Integer Programming (MIP) applied to a two-area electricity system using nodal-pricing mechanism for congestions. Reference [16] presents a study of an electricity system composed of 6 nodes, with two different zonal organizations. This study centers in the potential economic inefficiencies that may arise in each organization. A comparison between counter-trading and market coupling is applied to the North-Western European (NWE) electricity market in [17]. In his later works, the author in [18] analyzes a hybrid approach for congestion management in electricity systems. This method combines the characteristics of both implicit and explicit auctions. In addition, he studies the formation of the conjectures. As a result, the conjectured price response is function of the state of the network. Thus, the firms' strategic behavior presents discontinuities when the state of the network changes. As some of the references above, this study centers in a two-area system. Furthermore, [19] and [20], a centralized market splitting algorithm is implemented to model an integrated European market. The model is formulated as a mixed integer linear programming problem (MILP). The case study where the model is implemented is composed of 42 bidding areas. However, the model is aimed for a short-term analysis of the market. Finally, in [21], an agent based simulation model is used for assessing how market coupling mechanisms impact on the economic welfare in Europe in the long-term. This model is primarily focused on the CWE region, and more specifically in four countries: Germany, France, Belgium, and the Netherlands.

While most of the studies above have created equilibrium market models, not many of them address market equilibrium in a multi-area system incorporating an accurate representation of the technical and economical characteristics of the system.

This research aims at providing an efficient methodology to model the market equilibrium in a multi-area electricity system under non-perfect competition in a medium-term horizon. In particular, this methodology is applied to the European Internal Electricity Market (IEM), integrating the electricity markets already existing in the European countries. Beginning from the conjectural-variation-based market equilibrium model developed in [22] and [23], this paper extends it to a multiple area system in such a way as to capture the state of the interconnections between the different areas.

The remainder of the paper is structured as follows: Section II describes the market equilibrium used. Section III introduces the methodology for tackling this problem. Meanwhile, Section IV analyzes the application of the proposed methodology to the case study presented, as well as the results obtained. Finally, a summary of the conclusions and future work planning is provided in Section V.

II. MARKET EQUILIBRIUM MODEL

The focus of this paper remains on the use of the CV-based equilibrium model developed in [22] and [23]. Under the CV-based approach, companies form a conjecture about the reaction of their competitors at their own changes of quantities or price. In this way, the conjectures measure the interdependence among companies [24]. In [25] an overview of the main methods to calculate these conjectures is presented. The conjectures are usually taken as an exogenous variable based on historic data [26–28]. Nevertheless, several recent studies have shown the way to calculate the conjectures endogenously [29]. These models have been widely studied in the literature: [22, 26, 30]. An important feature of this method for modeling market equilibrium is the flexibility that it provides for analyzing different degrees of competition, from perfect competition to Cournot oligopoly.

Guided by this approach, and considering the European electricity market to be non-perfect, different agents' strategic behaviors may appear depending on the state of the interconnections. For instance, congestions in the interconnection can allow some market participants to gain market power in certain regions. In addition, the agents' strategies may also be influenced by forecasts on renewable generation. Hence, the objective is to model the market power from any market agent, and their strategies under different situations in regard to the state of the interconnections. When modeling this effect, the idea is to characterize each strategy by means of a conjectured price response, as a function of the state of the network. In this sense, a special effort must be made in determining the right conjectures to achieve realistic results.

For the sake of clarity, this paper takes a different way to model the reaction of the competitors' strategies by assigning different price spreads to each agent depending on the state of the interconnection, unlike the model in [22], where the conjectured price response is defined as a function of the supply. As a consequence, the resulting model objective's function is modified, becoming a linear problem, rather than a quadratic one. This approach may help to perceive the price response in a more intuitive way. In addition, it remains equivalent to the other, and can be used indistinctly. It could even be included in the other, and apply it one way or another depending on the market agent, or area.

The rest of this section aims at describing the market model used. Hereafter, a is used to denote the different areas considered in the problem, p represents the set of periods or load levels, i denotes the market agents that participate in the system and l is used to define the interconnections present in the system.

Parameters:

$D_{a,p}$	demand in area a in period p
$C_{i,a,p}$	cost function for agent i in area a in period p
$S_{i,a,p}$	price spread for agent i in area a in period p
$H_{a,l}$	matrix where a correspondence between areas and interconnections is defined as follows: • 1 if interconnection l starts in area a • -1 if interconnection l ends in area a • 0 if interconnection l does not correspond with area a
$\underline{F_l}$	minimum power flow in interconnection l
$\overline{F_l}$	maximum power flow in interconnection l
$\underline{P_{i,a}}$	minimum power produced by agent i in area a
$\overline{P_{i,a}}$	maximum power produced by agent i in area a

Decision variables:

$P_{i,a,p}$	power for agent i in area a for period p
$f_{l,p}$	power flow in interconnection l for period p

Taking the approach of spread increments over the equilibrium price or perfect competition, the optimization problem can be written as:

$$\min_{P_{i,a,p}} \sum_i \left\{ \sum_a \sum_p C_{i,a,p}\left(P_{i,a,p}\right) + S_{i,a,p} P_{i,a,p} \right\} \qquad (1)$$

s.t.:

$$\sum_i P_{i,a,p} - \sum_i H_{a,l} f_{l,p} = D_{a,p} \; : \; \lambda_{a,p} \qquad \forall a, \forall l \qquad (2)$$

$$\underline{F_l} \le f_{l,p} \le \overline{F_l} \qquad \forall l, \forall p \qquad (3)$$

$$\underline{P_{i,a}} \le P_{i,a,p} \le \overline{P_{i,a}} \qquad \forall i, \forall a, \forall l \qquad (4)$$

The price $\lambda_{a,p}$ is the dual variable of the demand balance equation (2), and can be stated as[2]:

$$\lambda_{a,p} = \frac{\partial C_{i,a,p}\left(P_{i,a,p}\right)}{\partial P_{i,a,p}} + S_{i,a,p} \qquad \forall i, \forall a, \forall l \qquad (5)$$

The set of equations (1)-(4) provides the main optimization model and includes only the fundamental equations that characterize it. The rest of the constraints containing all the technical characteristics of the considered systems, such as the technical constraints of the operation of all thermal and hydro units (variable costs, emission limits, maximum and minimum power, efficiency, etc.), have been taken into account but were not shown here.

III. NETWORK CONFIGURATIONS REDUCTION METHODOLOGY

In the region of Europe considered in this paper (details in Section IV), there are 13 interconnections between countries. In this situation, the possible number of states of the interconnections (hereinafter referred to as network configurations) is 2^{13} that yields a total of 8,192 cases. Therefore, in order to make the proposed optimization market model viable in the decision-making process, it is decisive to implement an efficient methodology that reduces the huge number of possible network configurations, obtaining the most usual states of the interconnections without a major loss of accuracy. In this context, a technique similar to the one previously introduced in [31] was developed. The purpose of this study goes further than [31], actually incorporating the resulted network configurations into an equilibrium model for the European electricity market.

The procedure implemented in this paper relies on the medium-term equilibrium model developed in [22], computed using the so-called system states, technique introduced in [32] that replaces the traditional load levels, and allows for faster execution times with almost no accuracy loss. A system state in this context defines a set of individual time periods (hours in this problem) in a specified horizon (months) that share similar characteristics in terms of a determined system feature, in this case the net demand. The main advantage of this approach over the classical representation of load levels rests on the capabilities with system states of incorporating chronological information between the chosen time periods. That thereby derives in a better capture of the outcomes of the electricity market.

The methodology can be divided in two phases:

A. Phase 1: Extracting the main network configurations

Initially, the equilibrium is found under perfect competition using for this execution a compromise number of system states, that satisfies both the accuracy of the solution and the computational power necessary to run the model. Once completed, the outputs of the model provide hourly prices per area considered for all the horizon. These prices will determine the state of the interconnections for each hour, thereby corresponding to a particular configuration of the network.

In this sense, a network configuration is defined by the state of the interconnections among the countries considered

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[2] Only if the duration of p is 1 hour. Otherwise, it should be divided by the duration of the load levels.

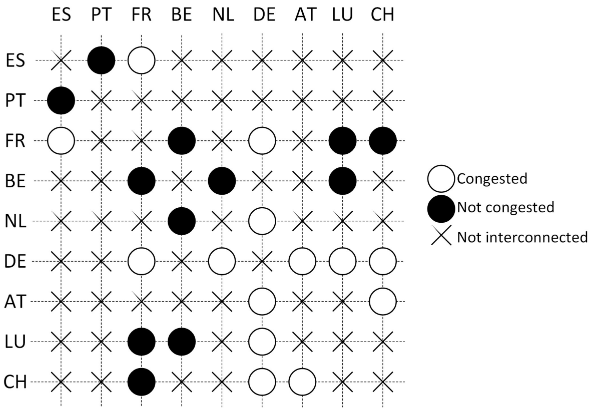

Fig. 1: Example of a network configuration: state of the interconnections corresponding to the main network configuration **1** in Section IV

in terms of congestion, as exemplified in Fig. 1. This situation can also be represented as a symmetric matrix $N \times N$ (N equals the number of countries studied), where each element a_{mn} corresponds to the state of the interconnection between country m and country n, taking the value of 0 when congested and 1 otherwise. In case there is not an interconnection between country m and country n, the element a_{mn} takes the value of 0.

$$\begin{pmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{mn} \end{pmatrix} \tag{6}$$

Throughout the horizon of the problem there will be configurations that are repeated for different hours. In addition, there are configurations more representative than others. The objective of this section is to determine which are the configurations of the network with more presence (Fig. 2), for the purpose of reducing the dimension of the problem under non-perfect competition conditions.

With the goal of determining which of the configurations are the main representatives, a clustering algorithm for categorical data was developed. This procedure groups the configurations based on their frequency and the similarity between them. The rules used to measure the similarity among configurations are built on weight assignations based on historical values of the total annual demand of each area, in such a way that establishes priorities depending on the share each area accounts for in the whole system.

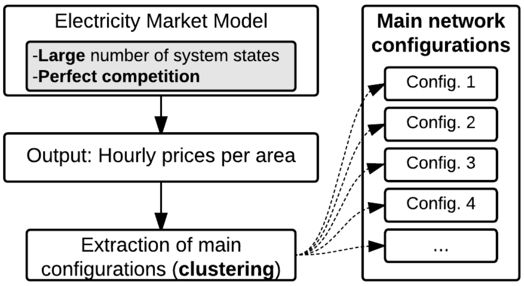

Fig. 2: Diagram of phase 1 of the methodology: extracting the main network configurations

The measurement of similarity between configurations is established as follows: each area is characterized by a weight, assumed as a function of its historical annual demand. With N areas, there are 2^N possible combinations of grouping them, and each possible set can be identified by the aggregated weight of all the areas within the set. The similarity list is created ordering all these possible sets in ascending aggregated weight. Therefore, the first set will be composed of the country with lowest annual demand and the last one will comprise all the countries.

With this information, the similarity matrix can be built. It defines the similarity relationship between all the unique configurations extracted from the hourly prices.

Once identified the similarity matrix, the clustering algorithm works as follows: starting from the configuration with the lowest frequency, the most similar configuration is obtained through the similarity matrix. The former is grouped into the latter, thus increasing its frequency, and removed from the collection for the rest of the process. This procedure is repeated for all the configurations until the number of remaining configurations reaches the number of main configurations predefined by the user.

The analysis of the main network configurations will give an outlook of the possible congestions that may arise between areas, and more information about the resulting prices in the different zones. Thus, for each of the found network configurations, it is now possible to assign a price spread increment for each agent based on conjectured price responses. For instance, an agent in an isolated area could exercise market power influencing this way the price in its location with an increase.

B. Phase 2: Assigning main configurations to the results of a perfect competition equilibrium.

Continuing with the methodology, when the most representative configurations have been obtained, the perfect competition model is run again, this time under normal conditions in terms of number of systems states (significantly less than the number used in the initial computation of phase 1), which yield a solution notably quicker. Consecutively, the resulting hourly prices for each country are identified to the nearest main network configuration (extracted in Phase 1) though a classification algorithm, as shown in Fig. 3.

This algorithm first attempts to match each state of the network directly with one of the main network configurations. In case there is not a direct association, the maximum price spread specified to consider the interconnection not congested is gradually widened until the studied configuration converges towards one of the main ones, always ensuring to be within the acceptable range of congestion price spread. However, if after this process, the configuration did not converge into a representative one, it is associated to the most similar representative; this step is computed with the similarity measures previously described.

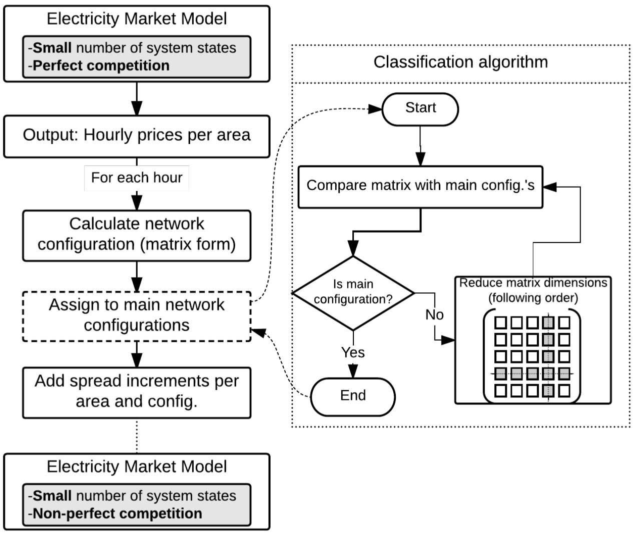

Fig. 3: Diagram of phase 2 of the methodology: procedure steps after obtaining the main network configurations

In practice, the procedure functions in the following way: each hour corresponds to a network configuration, that can be represented in matrix form. This matrix is matched against the reciprocal matrices of the main representatives. If it does not match either directly or through the spread opening, the matrix dimensions are reduced: starting from the set with the lowest aggregated weight in the similarity list, the rows and columns of the matrix corresponding to the areas within the set are not considered in the comparison. The procedure will repeat this process with the next sets in the list one by one until a match is found.

Finally, once the assignation is completed, each hour has a direct correspondence with a network configuration, that in turn has a spread increment associated with each area, imposed as an input by the user. With these two relationships, it is now possible to run the model in non-perfect competition conditions.

In essence, this representation may allow for efficiently computing a non-perfect competition model composed of large single markets linked under a unified framework, with multiple market splitting options.

IV. CASE STUDY AND RESULTS

This section presents a case study where the proposed methodology is implemented. In Section IV.A, the electric power system used in this case study is described. Moreover, the implementation of the methodology is explained in Section IV.B. Finally, Section IV.C gives the results obtained after running the model under non-perfect competition.

A. System description

For this case study, the countries which belong to the Iberian and CWE electricity markets were considered. Those include Portugal, Spain, France, Switzerland, Austria, Luxembourg, Belgium, Germany, and the Netherlands, as shown in Fig. 4.

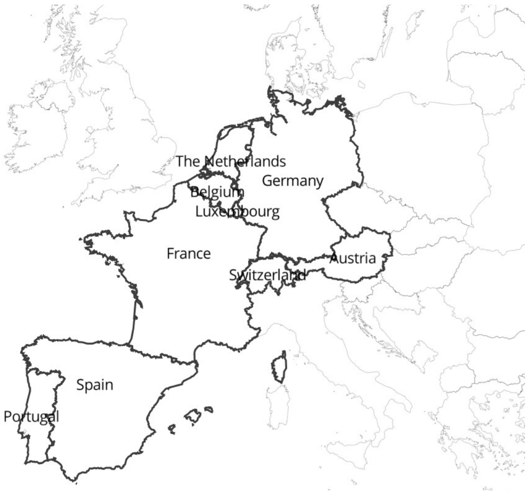

Fig. 4: European countries considered in the case study

If taken individually, each separate country is typically represented as a single-price market model, characterized by not considering network constraints initially and consequently, the market price be the same country-wide. In these systems, congestions are managed through additional mechanisms aimed at resolving technical requirements. The main assumption in single-price models is that they do not internalize the effects of network congestion in generators' strategic behavior. This behavior, but taken among countries, is precisely the objective of study when integrating each separate area into the complete system, constituting the Europe electricity market. This resulting system constitutes a zonal pricing market, in which should congestion be ignored, the price will be the same in the whole system.

The selected horizon is about two years, from February 2016 to December 2017, since the model is geared to the planning and analysis of operations for decision making in the medium term. This scope is adequate to represent the medium-term evolution of the market in the European countries considered. Moreover, the model incorporates all the information regarding the technical and economical characteristics of the system, such as market agents, units, technologies, etc.

B. Network configurations methodology implementation

After the model inputs are set up, and following the methodology explained in Section III.A, a perfect competitive model was computed using 80 systems states of net demand by month. Consecutively, the resulting hourly electricity prices for the period considered (16,800 hours) were gathered. The selection of 80 states was found to be a good trade-off in terms of accuracy of representation of the data, and computational requirements for the computer used[3] (Fig. 5). As a result, it allows for capturing a wider range of prices while not ensuing in a very time-consuming process. Under

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[3] The computer used had the following technical characteristics: Intel® Xeon® CPU E5-2660 v3 @2.60GHz with 40 logical processors and 144 GB of installed RAM memory. The operative system running was a 64-bit Windows Server 2012 R2.

such conditions, the execution led to an optimization problem with 15,254,011 variables and 7,623,372 equations, which required a maximum memory of 15.65 GB and a total execution time of 1169 seconds.

On the collected hourly prices, an analysis of the network configurations present in each hour was carried out. As the number of the hours executed is high enough for a medium-term horizon, it is quite frequent that the same network configurations are repeated for different hours. In addition, there are configurations more representative than others. The previous instruction led to 95 unique states of the interconnections. Consecutively, a secondary analysis based on the clustering algorithm in Phase 1 was performed. After the evaluation, eight main representatives were chosen as a good compromise between the error (computed as the aggregated dissimilarity in the clustering process) against the number of clusters used (Fig. 6).

A great reduction has been achieved: from 8,192 possible states of the interconnection to only eight. It would be only necessary to introduce the price response of the market agents in the eight representative network configurations to obtain a reliable representation of the system without a major loss of accuracy in the results.

Withal, the strategic behavior of market agents is clearly influenced by demand or wind conditions and forecasts. Therefore, the number of main network configurations will depend to a great extent on the data contemplated as well as on the values of the inputs subject to uncertainty, such as demand and wind.

In Fig. 7 the eight representative network configurations are shown, accompanied with the percentage of hours following this pattern. When these configurations are compared with the ones obtained in [31], some differences are noticed. This transformation is due to the quickly changing electricity markets in Europe. Data differ almost three years from one study to another. Many factors, either in terms of regulatory changes, technical modifications of the system or others, can make prices change significantly over the time.

Therefore, the definition of the network configurations (indicated in Fig. 2) is not expected to be run only once, and subsequently use these results into the model for the following years. This analysis is meant to be repeated from time to time, about once per year if necessary or when significant structural changes in the electricity market occur, to update the main network configurations in Europe, and that way avoiding a lack of precision. In contrast, after the network configurations are obtained, the rest of the methodology (marked in Fig. 3) is intended to be applied within the ordinary operation of the agent for decision-making.

As part of the procedure, following to the second phase of the methodology, next step consisted of computing the model in perfect competition with 10 states per month. This number was fixed for simplicity purposes as the appropriate number of systems states with what run the model. However, the optimum number of states that meet the requirements set in commercial applications for decision-making is usually bigger, for a better accuracy of the results. On these basis, the resulting model consisted of a problem with 2,004,611 variables and 937,205 equations that consumed 1.55 GB of memory and took 218 seconds to complete, considerably lower than the first part of the methodology, and thereby more suitable for a more frequent execution of the model.

Building on the methodology in Section 0, the classification algorithm is applied to the output hourly electricity prices in order to assign each one of the prices per area to one of the main configurations found.

After the classification is established, about 75% of the resulted prices were assigned directly to one of the eight main configurations, while all the rest were either assigned by widening the price spread or by proximity with the representative which most closely resembled the states of the interconnections in the system.

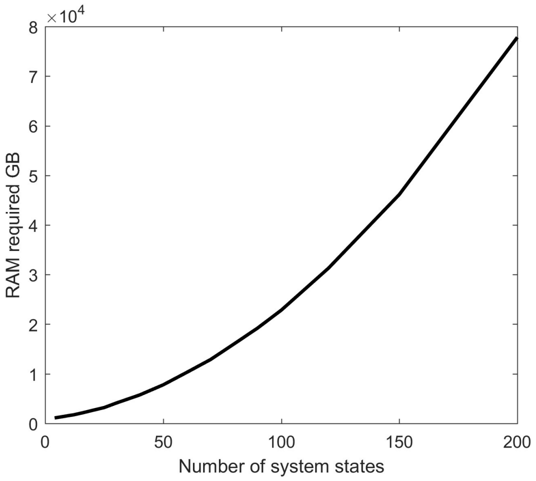


Fig. 5: Trade-off curve between the number of system states defined in the model against the RAM memory required for execution

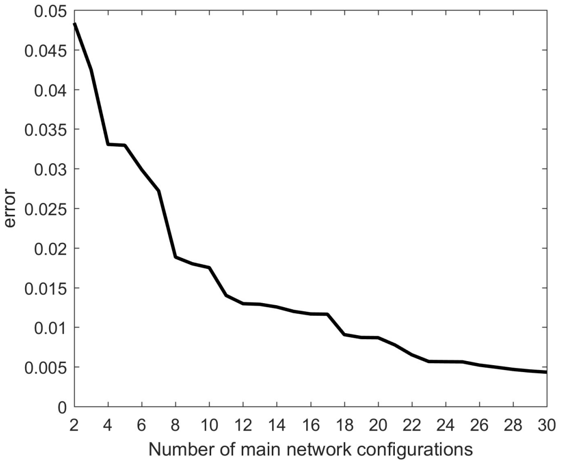
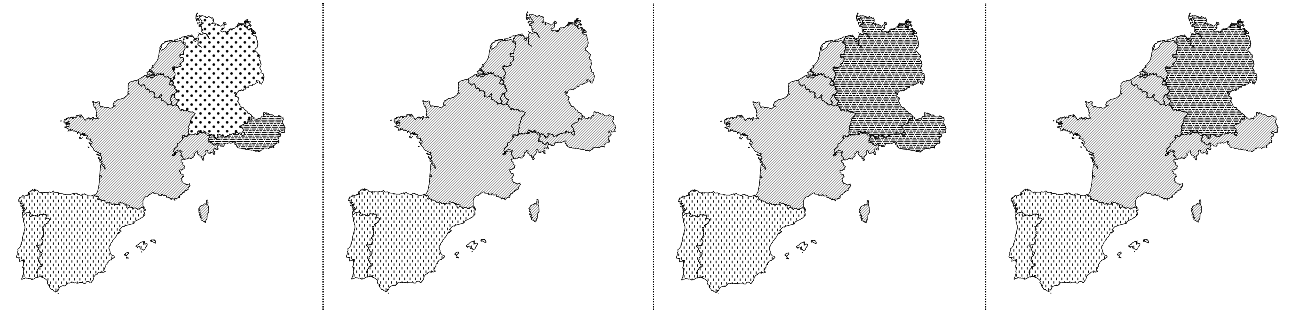
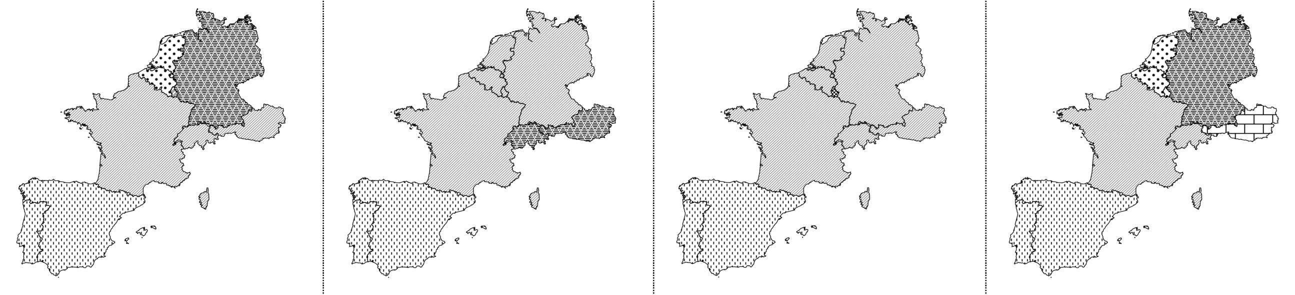


Fig. 6: Trade-off curve between the number of main network configurations against the accumulated error



Network configuration **1**: 28.48% | Network configuration **2**: 21.20% | Network configuration **3**: 21.14% | Network configuration **4**: 10.49%



Network configuration **5**: 9.84% | Network configuration 6: 3.48% | Network configuration **7**: 2.88% | Network configuration **8**: 2.50%

Fig. 7: Eight main network configurations

With this association, and once the price spread increments are defined per market agent for every one of the main network configurations, the model would be prepared to be run under non-perfect competition.

C. *Model under non-perfect competition*

This subsection provides the obtained results after executing the model under non-perfect competition. In pursuit of simplicity and comprehensiveness, the following analysis is focused on just one area (Belgium) and for one month within the horizon of the problem (March 2016). In addition, only one company for each area has been modelled.

TABLE 1: CAPACITY OF BELGIUM INTERCONNECTIONS

Interconnection	Capacity (MW)
Belgium-France	4081
Belgium-The Netherlands	2900
Belgium-Luxembourg	550

To put the analysis in context, Belgium is linked to its neighbor countries by three interconnections: with France, the Netherlands, and Luxembourg. The capacities used in the model are listed in Table 1. As may be seen, there is a significantly larger interconnection with France than with the other two countries. It is also worth noting that although Belgium shares border with Germany, there is not an interconnection that links their electricity transmission systems. However, as its other neighbors are greatly interconnected with Germany, the electricity prices in this country have a great impact in Belgium too.

Looking at the main network configurations obtained in Fig. 7, the only ones where none of the mentioned interconnections are congested are configurations 2 and 6. Additionally, in configuration 7 only the interconnection with Luxembourg is congested. In the cases above and in this last one, since the capacity of this interconnection is very low in comparison with the others, the configurations of the network do not enable the market agent of Belgium to exercise any sort of market power, and consequently the spread increment will be close to 0.

As regards the remaining configurations, the interconnection with Germany (indirectly through the Netherlands) is congested in every case. This situation will facilitate the agent in Belgium to increase market power in its area that in turn, will rise its electricity price. Furthermore, in both configurations 5 and 8, the interconnection with France is congested too. In these cases, the system Belgium-The Netherlands find itself partially isolated. This isolation can become very large in the situation that the interconnection between the Netherlands and Germany were congested too. In such a case, the price in Belgium would be different, the market power would increase, thus giving rise to a greater spread increment.

TABLE 2: DISTRIBUTION OF HOURS IN MARCH 2016 ACROSS THE MAIN CONFIGURATIONS

Network configuration	Number of hours
Config. 1	79
Config. 2	297
Config. 3	86
Config. 4	58
Config. 5	119
Config. 6	0
Config. 7	0
Config. 8	105

Empirically observing the electricity market in Europe, reasonable values of spread increments per day and configuration have been adjusted and introduced in the model for Belgium agent in March 2016. If the objective was to model a real-size case, the estimation of the spread increments is of great relevance. There are complex ways to estimate these values, by means of historical values, or fundamental variables as wind, nuclear, etc. However, this case study is meant to serve as an example just to illustrate the proposed methodology and the impact that spread increments have on the outputs.

TABLE 3: AVERAGE BELGIUM ELECTRICITY PRICE IN MARCH 2016 FOR PERFECT AND NON-PERFECT COMPETITION EXECUTIONS

Perfect Competition	**Non-perfect competition**
24.52	26.49

Once the model has been executed for non-perfect competition, Table 3 provides the average electricity price in Belgium for March 2016 under non-perfect competition, compared with the results in perfect competition. On the one hand, as can be drawn from Table 3, the model has been correctly calibrated, since the monthly baseload price is similar to the real spot price for that month (27.13 €/MWh). On the other hand, looking at the distribution of the total hours in March 2016 across the main configurations (Table 2), it is also reasonable to have a greater price under non-perfect competition, since the main configurations in these months correspond to states of the network where the market power exercise in Belgium is bigger, and also the associated spread increment.

So as to best describe this effect, the hours in a specific day have been extracted in Fig. 8. As can be appreciated, the highlighted hours showing a price increase are relating to configuration 5. As mentioned above, the price spread increment for this configuration is high, since the system Belgium-The Netherlands is isolated from the other areas, as all the interconnections with them are saturated. Therefore, the results are very reasonable.

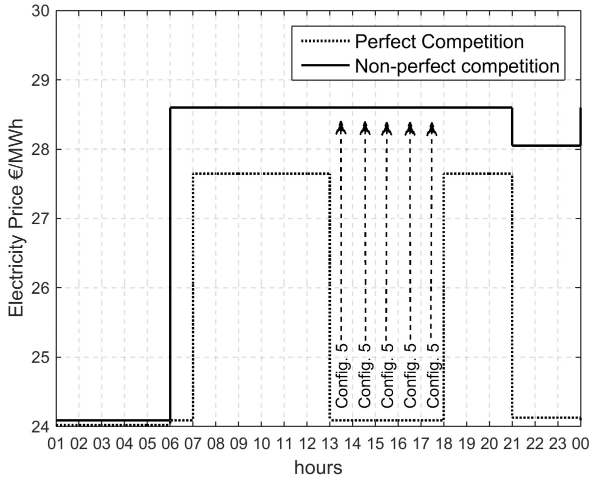


Fig. 8: Electricity price in Belgium of selected day in March 2016: effect of spread increment in peak hours, respect to perfect competition

It is worth noting that the objective with this model is not to achieve an hourly pattern of the electricity price, since the model is targeted to a medium-term operation and planning of the electricity market. Furthermore, the results in this case study have been obtained using a small number of system states. Therefore, the results showed in this section are reasonable from the perspective of this paper.

V. CONCLUSIONS

In conclusion, this paper is innovative since it proposes an efficient approach to compute a non-perfect competition model composed of large single markets linked under a unified framework, with multiple market splitting options.

A case study was presented where this methodology was able to reduce considerably the possible states of the interconnections yet maintaining the accuracy thereby making the problem under non-perfect competition computationally tractable.

The application of this research is focused on a real-size case study of Europe where some assumptions has been made for the sake of clarity. With the recent creation of the Internal Electricity Market in Europe, this area could bring much insight for generators and system operators' entities, thanks to the representation of a complete European market. However, this methodology could be also equally generalized to any system with multiple areas, as it is the case in some parts of the United States, Latin America countries, and even Italy, whose electricity market is divided in nodal-price regions. Therefore, this line remains as an interesting area of research with a lot of potential.

Among the next future steps, it would be interesting to apply the proposed methodology in a real system estimating the conjectures that truly reflect the behavior of the market participants. This methodology would offer a robust and efficient way to analyze the effect of regulation foresight as well as changes in the operation of the electric market at a European level.

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