Energy Economics 75 (2018) 583–601

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Consistent and robust delimitation of price zones under uncertainty with an application to Central Western Europe☆

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ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form 31 August 2018
Accepted 14 September 2018
Available online 23 September 2018

JEL classification:
C38
C61
D47
L51
Q41
Q48

Keywords:
Cluster analysis
Electricity market design
Nodal pricing
Zonal pricing
Congestion management
Price zone configuration
Bidding zone configuration

ABSTRACT

New and alternative delimitations of price zones for Central Western Europe (CWE) might constitute a mid-term solution to cope with the increasing congestion in the electricity transmission grids. The significantly growing infeed from renewable energy sources puts more and more pressure on the grid and emphasizes the need for improved congestion management. Thus, a new delimitation of price zones is frequently considered in current discussions and research. The present paper applies a novel hierarchical cluster algorithm that clusters locational marginal prices and weights nodes depending on their demand- and supply situation to identify possible new price zone configurations (PZCs). The algorithm is applied in a scenario analysis of six scenarios reflecting main drivers that influence the future development of European Electricity markets in line with the trilemma of energy policy targets. Robustness of the new configuration is an important criterion for price zone configurations according to the European Guideline on Capacity Allocation and Congestion Management (CACM). Therefore, a robust price zone configuration is computed taking into account all the six individual scenarios. Results show that shape, size and price variations of price zones on the one hand strongly depend on the individual scenario. On the other hand, the identified robust configuration is shown to outperform other configurations, particularly also the current price zone configuration in CWE.

1. Introduction and literature review

The face of electricity markets is constantly evolving. E.g. in 2015, Flow-Based-Market-Coupling has been introduced in Central Western Europe (CWE) and the extension to Central Eastern Europe is already in planning. The continuously growing capacities of renewables imply also a shift in generation locations and increasing fluctuating infeed. This has a severe impact on the congestion situation and grid operations. In Germany, redispatch costs more than tripled from 2012 to 2015 (Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW), 2017). Therefore, new frameworks for the European Electricity markets are currently discussed in the literature and in the political arena. A potential solution is to reshape present price zones (bidding zones). Currently, a large ENTSO-E bidding zone study is undertaken that shall give insights into the effects of redesigned price zones in Europe (ENTSO-E, 2017). So far, national borders often align with borders of price zones. That might not be the optimal solution, as national borders do not necessarily reflect congestions in the grid.

The optimal solution for congestion management is often considered to be obtained via locational marginal pricing (nodal pricing), as nodal prices do not only reflect demand and supply characteristics but also congestions in the electricity grid (Hogan, 1992; Stoft, 1997; Egerer et al., 2016). According to Egerer et al. (2016), a single, uniform price for a zone might reflect wrong price information, since internal congestions and bottlenecks are not transparent. Neuhoff et al. (2013) support the preceding findings stating that locational marginal prices (LMPs) lead to a more efficient grid utilization resulting in significant cost savings. Also, Bertsch et al. (2015) investigate a zonal and nodal approach and conclude that LMPs are the best solution. Other configurations, e.g. zonal pricing or uniform pricing, would cause an increase of system costs of up to 4.6%. Ding and Fuller (2005) describe nodal pricing as the economically most efficient method as well, but also state that locational marginal pricing goes along with complex and complicated processes like data processing, accounting and financial settlements. Walton and Tabors (1996) investigate a variance criterion, namely the

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https://doi.org/10.1016/j.eneco.2018.09.012
0140-9883/

variance of LMPs between and within aggregated zones to evaluate zonal configurations, i.e. to reduce the amount of nodes in the Western Systems Coordinating Council (WSCC) system from 3500 to 20. The most well-known example for a system using LMP is Pennsylvania New Jersey Maryland Interconnection LLC (PJM) in the United States, but also most other deregulated electricity markets in the US use LMPs. Several price zones within one country can be found in Europe in Scandinavia where Norway, Sweden and Denmark are split into different price zones.

Currently, a zonal approach that aggregates similar nodal prices to zones seems to be more readily applicable in Europe, since the implementation of nodal pricing generally requires the establishment of an independent system operator (ISO) who combines the role of market operator with (at least) part of the grid operation. The European guideline on Capacity Allocation and Congestion Management for Electricity (CACM) identifies evaluation criteria for future price (bidding) zone configurations. The main criteria are liquidity, market power, stability, robustness, network security and unbiasedness of prices in the new price zones. Before applying the criteria and analysing the results, a new configuration of price zones obviously has to be identified.

Yet, a closed optimization of price zone delimitations on a complex grid of (Central Western-) Europe with it's over 2000 nodes appears not feasible, especially in an adequate amount of time, due to the problem structure with numerous binary variables and highly non-linear constraints (Breuer, 2014). Therefore, closed optimization focus on rather small scale examples as shown in Grimm et al. (2017). For large-scale applications heuristics in form of cluster algorithms are applied.

The paper at hand focusses on such an algorithm. Among a few others, two major methods have been developed in recent publications to delimitate new price zones. The first one is to cluster the aforementioned LMPs to zones with similar prices, the other method refers to clustering of Power-Transfer-Distribution-Factors (PTDF). Within these two possibilities, various types of cluster algorithms have been applied, e.g. hierarchical, genetic or partition algorithms such as fuzzy-k-means (Yang and Zhou, 2006). Also, underlying models vary from large scale applications to small examples like IEEE-test cases.

Clustering of LMPs is applied by Imran and Bialek (2008), Burstedde (2012), Breuer et al. (2013), Wawrzyniak et al. (2013), and Breuer and Moser (2014). Breuer and Moser (2014) use a genetic algorithm and apply the algorithm to a large scale model of the European transmission system for the years 2016 and 2018. They investigate redispatch costs, network security and also changing price zones depending on seasons. In contrast, Burstedde (2012) applies a hierarchical algorithm based on Ward's criterion to a simplified model of the European transmission system with 72 nodes. In addition, two different scenario years (2015 and 2020) are investigated and evaluated e.g. using total system costs. Imran and Bialek (2008) present three different approaches to cluster LMPs notably geographical clustering, fuzzy-c-means and price differential clustering. Wawrzyniak et al. (2013) investigate zonal solutions based on LMPs for different wind scenarios on a Polish nodal system.

In contrast to the LMP-method Duthaler (2012), Kang et al. (2013), Klos et al. (2014), Kłos et al. (2015), Sarfati et al. (2015) and Van Den Bergh et al. (2016) apply cluster algorithms based on PTDF-values. Kłos et al. (2015) aim to reduce loop effects by clustering PTDF values. Their methodology refers to the mentioned goal of CACM to minimize adverse effects of internal transactions on other price zones. A similar approach is utilized by Van Den Bergh et al. (2016). The authors cluster PTDF values on selected critical branches and, after investigating a base scenario, analyse several delimitations with different amounts of price zones. Klos et al. (2014) identify critical branches using a clustering based on KKT-multipliers first and cluster PTDF-values afterwards. Kang et al. (2013) investigate the IEEE-39 system for a given number of zones. Sarfati et al. (2015) consider new delimitations based on five indicators, e.g. loop flows or price convergence on a 32-node model of the Nordic system. Also, three different wind-infeed scenarios are investigated.

Obviously, uncertainties strongly influence the delimitation of price zones. The dispatch of power plants, which depends mostly on variable costs, but also the development of demand, grid development and expansion of renewable energy sources (RES) affect congestions in the electrical grid, which in turn affect the LMPs and PTDF-values. Developments of all aforementioned factors may be related to the political choices made, which notably reflect the priority accorded to the different objectives within the triangle of energy policy targets (energy policy trilemma), namely security of supply, sustainability and economic efficiency (Spiecker and Weber, 2014).

Given these uncertainties and under consideration of the different clustering approaches and underlying models, the major contributions of the present paper are three-fold. First, the applied cluster algorithm has a clear economic foundation and objective, namely the minimization of price variations within the newly formed price zones. Second, a novel hierarchical cluster algorithm is applied, that weights nodes according to their relevance in terms of infeed and demand. By doing so, the importance of different nodes is acknowledged. All this is applied on a large-scale electricity system, namely the CWE system. Third, several different scenarios are considered for a single year (2020). The scenarios are derived by varying not only one but five different key drivers for electricity markets. This corresponds to an operationalisation of the robustness criterion for price zones referred to in Article 33 of the CACM guideline. The guideline mentions robustness and stability of price zones as relevant criteria without providing clear definitions nor a delimitation between the two. Hence robustness is understood here as referring to uncertainties within one period (year), whereas stability is interpreted as absence of (or limited) changes over time. Stability is not considered further here, yet could be treated within the same framework.

The remainder of the article is organized as follows: Section 2 outlines the developed methodology. First a general overview is given. Then the cluster algorithm is described, followed by the scenario construction and the evaluation methodology. Section 3 presents the application and the utilized grid- and generation models as well as the parameters retained for the different scenarios. The obtained results are then presented and discussed in Section 4. Notably standard bidding zone configurations are compared to the robust one. Furthermore, the results are also compared to the current price zone configuration (PZC) with five price zones in the (extended) CWE region (Switzerland, Netherlands, Belgium, France and Germany-Austria-Luxembourg). Note that Switzerland being not part of the EU is to date not member of the electric CWE region. Given the strong electrical interconnections it has both with France and Germany (lines to Austria are less developed), it is yet subsequently included in the analysis.

2. Methodology

As stated in the introduction, solving the problem of how to design optimal PZCs on a large-scale grid model in a scenario analysis is a computationally and mathematically challenging (cf. Murtagh and Legendre, 2014). Hence, we apply a specifically-designed hierarchical cluster algorithm to obtain optimized sequences of PZCs.

The overall methodology of this paper is sketched in Fig. 1. The core of the methodology consists of the developed hierarchical cluster algorithm which is therefore presented first in Section 2.1. The algorithm performs a stepwise aggregation of nodes to zones based on similarity of nodal prices. At each step of the aggregation, a new PZC is obtained and the algorithm may be stopped at any desired number of zones. The cluster algorithm is fed with input parameters, namely LMPs, and enables also the calculation of so-called “robust” PZCs by inserting LMPs from various scenarios simultaneously into the algorithm.[1]

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[1] Cf. Section 4.4.3 for a discussion whether this configuration is robust in a mathematical sense.