

Schönheit, David; Bruninx, Kenneth; Kenis, Michiel; Möst, Dominik

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Improved selection of critical network elements for flow-based market coupling based on congestion patterns

David Schöheit^{*†}

Kenneth Bruninx^{‡§¶}
Dominik Möst^{†‡}

Michiel Kenis^{‡§¶||}

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Abstract: Flow-based market coupling provides zonal day-ahead markets with appropriate signals of possible real-time congestions by incorporating information on local load and generation patterns. It relies on predictive parameters, notably the base case and generation shift keys. Also it only monitors part of the grid, through selecting critical network elements. In consequence, it naturally falls short of a nodal pricing-based cost-optimal solution. Based on a test network with three flow-based market coupling zones, we show that the results of flow-based market coupling converge to nodal pricing solutions with an increasing amount of re-configured market zones. We identify if re-configured market zones can help to improve the selection of critical network elements and lead to cost reductions even in the original market zone setting. We find that around 90% of the cost reductions from a market zone re-configuration can be maintained when the critical network elements, obtained from the re-configured market zones, are used for the original market zones. This is a strong indication that, both in reality as well as model-based research of flow-based market coupling, the selection of critical network elements should be based on expected congestion patterns. To find these congestions, we conduct a nodal price-based market zone re-configuration that helps to identify lines with different congestion signals. This approach can constitute a helpful addition to static and assumption-based selection criteria for critical network elements, such as the often-used zone-to-zone power transfer distribution factors that strongly rely on assumptions like generation shift keys.

Keywords: critical network elements, flow-based market coupling, market zones, nodal and zonal markets, zone re-configuration

JEL classifications: C61, D47, L94, Q41, Q43, Q47

1 Introduction: The relevance of market zone re-configuration

The European setup of bidding zone-based market coupling inherently comes with welfare losses (Aravena and Papavasiliou, 2016). Conversely, nodal pricing approaches lead to an optimal grid-constrained dispatch solution (Androcec et al., 2009). On average, zonal market clearing will result in a greater need for remedial actions, carried out in form of congestion management, e.g. redispatch and curtailment (other measures are discussed in e.g. Hosseini et al., 2016). Ensuring grid-compatible market outcomes, allowing welfare-enhancing cross-zonal trade while respecting cross-zonal and intra-zonal grid limitations (Poplavskaia et al., 2020), has become more challenging in several European countries with the expansion of renewable energy capacities. Greater redispatch and curtailment volumes reflect this trend (cf. Hirth and Glismann, 2018).

^{*}Corresponding author, david.schoenheit@tu-dresden.de, +49 351 463 39766

[†]Technische Universität Dresden, Chair of Energy Economics, Münchner Platz 3, 01069 Dresden, DE

[‡]kenneth.bruninx@kuleuven.be, michiel.kenis@kuleuven.be, dominik.moest@tu-dresden.de

[§]KU Leuven, Research Group Energy Systems Integration & Modeling, Celestijnenlaan 300A, B-3001 Leuven, BE

[¶]EnergyVille, Thor Park, Poort Genk 8310, B-3600 Genk, BE

^{||}Flemish Institute for Technological Research (VITO), Boeretang 200, B-2400 Mol, BE

Flow-based market coupling was introduced in Central Western Europe in 2015 with the goal of decreasing the divergence between commercial and physical flows. Its multi-step methodology accounts for grid constraints before and during market coupling by estimating grid utilization before market coupling, contained in base cases (two-days-ahead congestion forecasts), as well as changes in grid utilization due to changes in the export/import position of bidding zones, estimated by generation shift keys (GSKs). To provide appropriate cross-zonal trading capacities, flow-based market coupling monitors the flows and physical limitations of the grid elements that are most affected by trade, the so-called critical network elements (CNEs). This way, it sends more accurate congestion signals to the market and enables more trade, on average (Kristiansen, 2020).¹

Importantly, flow-based market coupling monitors *part* of the grid and makes simplifying assumptions about changes in nodal injections, therefore incorporating nodal information *imperfectly*. This imperfection is due to its reliance on discretionary parameters (base cases, GSKs, selection of CNEs) that drive the performance of flow-based market coupling. The approximate and predictive nature of these parameters is one of the reasons why the flow-based market coupling solution falls short of the nodal pricing solution (Aravena and Papavasiliou, 2016). A major goal of research and TSO activities is the correct design of these parameters, e.g. Van den Bergh and Delarue (2016) focusing on improved GSKs and Schönheit et al. (2020b), researching new methods for base case computations. The subject of this paper is the strategy to select critical network elements, a parameter of flow-based market coupling that has been mostly neglected by research.² We set out to *identify an improved selection of critical network elements, based on information from a hypothetical market zone re-configuration*.

To achieve this goal, 1) we show that the solution of flow-based market coupling (overall costs and congestion management) converges to the solution of nodal pricing with an increasing number of market zones. We base the re-configuration on the clustering of similar nodal prices to help better represent nodal prices (and thus congestion signals) within the new zones. Based on this 2) we identify an improved selection of CNE within flow-based market coupling, taking into account a higher granularity of market zones. We investigate if deriving CNEs based on re-configured market zones (that approach a nodal pricing solution) leads to cost reductions in flow-based market coupling even without realizing the zone re-configuration itself. This approach helps to identify intra-zonal lines as CNEs, especially when they become cross-border lines in the setting of re-configured market zones. We reveal that CNEs based on re-configured market zones (based on the proposed nodal price-based clustering of nodes) can help to achieve a large fraction of the cost reductions from the market zone re-configuration. The described, novel CNE selection process outperforms the regular CNE selection process based on zonal power transfer distribution factors (PTDFs) and a static threshold.

The reason for considering market zone re-configuration in the setting of selecting critical network elements is that, ideally, nodal prices fully express the cost of supplying electricity to the specific node. Thus, nodal prices can be ill-represented by a zonal market setup and can be very heterogeneous within a bidding zone. Generally, a zonal market setup leads to lower generation costs than a nodal pricing approach (Van den Bergh et al., 2016b). This is rooted in the fact that nodal pricing is always more constrained than a zonal market model, in form of physical grid limitations, leading to the utilization of power plants with greater marginal costs. Van den Bergh et al. (2016b) state that zonal market outcomes have to be corrected by congestion management, therefore, "[t]he sum of this redispatch cost and the zonal generation costs is at least as high as the nodal generation costs." A possible remedy to reduce the need for remedial actions in a zonal market-based setting is *market zone re-configuration* and market splitting, researched in numerous studies. For the task of defining new market zones, Chicco et al. (2019) provide an overview of the various clustering methods. Beside the issue of identifying a measure of similarity or dissimilarity to delimit new zones, the physical connection of newly formed zones is another major requirement. Chicco et al. (2019) point out that

¹ For a full depiction of flow-based market coupling see Van den Bergh et al. (2016a) and Schönheit et al. (2020b).

² Schönheit et al. (2020a) discuss the effect of different selection thresholds for critical network elements on market and congestion management results but remain in the standard selection process.

many clustering algorithms do not consider topology-based constraints, so the physical connection usually has to be verified a posteriori.

Examples of analyses on market zone re-configurations include Van den Bergh et al. (2016b), who analyze ten European countries in 2013 with the aim of finding zone configurations to reduce intra-zonal congestion. Nodes are clustered with similar impact on inter-zonal links (by means of PTDFs). The authors find considerable improvements in market outcomes with a greater amount of bidding zones such that fewer remedial actions are needed. The reduction of internal congestions is also supported by the findings of Felling and Weber (2016) and Fraunholz et al. (2021). In another example, Felling et al. (2019) analyze the CWE region and form zones based on a hierarchical clustering algorithm, combining the nodes based on similarity of locational marginal prices (LMP). These are retrieved from a DC (direct current) approximation-based optimal power flow. They state that with an increasing amount of market zones, the price variance decreases *within* zones and increases *between* zones. Felling et al. (2019) find a steady decline in redispatch costs but a non-monotonic decrease in system costs with a greater amount of market zones. The trend of higher generation costs and lower redispatch costs with growing number of zones is also observed by Breuer and Moser (2014).

The economic advantages of market zone re-configuration has been shown in the scientific literature but it easily become a matter of (inter)national politics and regulation. It not only involves the splitting of existing zones, often coinciding with country borders, but also strong deviations from existing borders (Breuer and Moser, 2014; Felling et al., 2019). Ideal market zones can therefore stretch over several countries. Also, re-configuring zones in the present has profound changes for future markets. Felling and Weber (2018) show that the shape and size of newly formed market zones differ between considered scenarios. However, the authors find robust configurations that outperform the current market zones in any setting. Fraunholz et al. (2021) state that an ideal German market splitting for 2020 may become outdated already after 2025, supporting the notion that market zone configuration is a dynamic issue dependent on the underlying power systems and changes within them.

Against this background, we analyze what information we can derive from market zone re-configuration for the selection of critical network elements, without realizing re-configuration itself. This analysis is structured as follows. Section 2 details the setup of this analysis and theoretical elements that are important for the remainder of the study. In Section 3, we describe and visualize the clustering and re-configuration of zones. The results are presented in Section 4, indicating the possible cost reduction of new market zones and what fraction of it can be maintained with the proposed CNE selection strategy. We conclude the analysis with Section 5.

2 Setup of analysis and model

This analysis is based on a test network (Barrios et al., 2015) and model, described and developed in Schönheit et al. (2020a) and provided with open access. It is a 100-bus network with three flow-based market coupling zones (97 nodes total) and three adjacent zones (one node each). The model is developed dynamically, e.g. new zone configurations can easily be provided and implemented via data files. In contrast to the default dataset, in this analysis all renewable energy capacities are doubled, which is referred to as the “very high variable renewable energy sources (vRES)” case in Schönheit et al. (2020a).

The first step in this analysis is the re-configuration of market zones, detailed in Section 3. The analysis includes 2, 6, 20 and 97 (one zone per node in the FBMC area) newly formed market zones using a clustering algorithm, which we elaborate in Section 3. In a second step, these re-configured market zones are analyzed, involving the computation of flow-based market coupling parameters, concretely computing generation shift keys and selecting critical network elements as well as conducting the three following modeling steps that capture flow-based market coupling. First, the base case (D-2) is computed by the TSOs to determine the transmission limits for trade. Second, the

day-ahead coupled market clearing is performed (D-1). Third, congestion management (D-0) occurs through redispatch and curtailment in case of congestion. The resulting costs for generation (during market coupling) and congestion management in all analyzed settings (described in greater detail in Table 1 and below) are juxtaposed with a default setting and a benchmark:

- *Default/original setting*: The flow-based market coupling results in the original setting are used as a default, i.e. the original market zones and "standard" determination of FBMC parameters, including critical network elements (detailed below).
- *Benchmark*: The results from a nodal pricing approach are used as a measure for the optimal outcome. The dispatch of all nodes is determined simultaneously, considering all grid constraints.

Table 1: Specifications and configurations of analyzed settings in this analysis

	Default / Original setting: FBMC with regular CNEs	Setting 1: FBMC with new market zones	Setting 2: FBMC with market zone-based CNEs	Setting 3: FBMC with regular CNE	Benchmark: Nodal pricing
		Section 4.1	Section 4.2	Section 4.3	
<i>Zone configuration</i>	Original (3 zones)	Newly configured (2, 6, 20, 97)	Original (3 zones)	Original (3 zones)	No zones
<i>Amount of CNEs</i>	42	25, 78, 178, 265/all	25, 78, 178, 265/all	25, 78, 178, 265/all	265/all
<i>Selection of CNEs</i>	Zone-to-zone PTDFs with one threshold: 10%	Zone-to-zone PTDFs with one threshold: 10%	Same CNEs as in setting 1	In comparison to setting 1 & 2: Zone-to-zone PTDFs with different thresholds: 14%, 4.65%, 2.05% and 0%	All lines automatically included
<i>Quantified effect</i>	—	Cost reductions due to market zone re-configuration	Cost reductions with CNEs from setting 1 but with original market zone configuration	Cost reductions with <i>amount</i> of CNEs from setting 1 but but with original market zone configuration and CNE selection process	—

The re-configuration of market zones are referred to as "setting 1" in this analysis. We test two more settings, "setting 2" and "setting 3" (described below). Increasing the number of market zones results in more selected critical network elements, and vice versa, namely 25 CNEs for 2 zones, 78 CNEs for 6 zones, 178 CNEs for 20 zones and 265 CNEs for 97 zones, which is equivalent to all lines within the FBMC area. More zones translate into more CNEs due to two reasons. First, we select cross-border lines as CNEs automatically in this analysis. With more zones, more borders form and hence, also more cross-border lines. Second, the endogenous CNE selection process is based on zone-to-zone PTDFs, as an indication how a line l is affected by bilateral trade between zones $z \in Z$. If the absolute value of such a zone-to-zone PTDF-value is above a pre-defined threshold (α) it is deemed critical, see (Eq. 1). With a greater amount of zones, more zone-to-zone combinations are tested. Therefore, the likelihood that a line is affected substantially by one of these combinations increases, especially because zones are becoming smaller and intra-zonal lines are moving closer to the borders.

$$|\text{PTDF}_{l,z,z'}| \geq \alpha \quad \forall z \in Z \quad \forall z' \in Z \setminus \{z\} \quad \forall l \in L \quad (1)$$

Thus, we have to test whether the effects of market zone re-configuration on markets and congestion management (in setting 1) are due to the newly formed zones or because we choose a different

and larger set of critical network elements. Therefore, we conduct model runs in the two additional, described settings. In setting 2, the CNEs selected with re-configured market zones (from setting 1) are used in the original market zone configuration of three zones. This setting is referred to as "3-zone FBMC with market zone-based CNEs." In setting 3, the original CNE selection process and market zones are maintained. However, the sensitivity for selecting CNEs is adjusted to result in the same amount of CNEs, derived from re-configured market zones (and used in setting 1/2). This setting is called "3-zone FBMC with regular CNEs." The sensitivity for selecting CNEs is 10% as a default setting and adjusted to 14%, 4.65%, 2.05% and 0% to yield 25, 78, 178 and 265/all CNEs, corresponding with the *amount* of CNEs from the newly configured market zones. The CNEs themselves, however, are not necessarily the same, since the selection process differs:

- In the regular CNE selection process (used in setting 3 and the default case), we have three zones and thus three zone-to-zone combinations that are checked: $3 \cdot (3 - 1)/2$. Different thresholds (α) are used in setting 3 (see above).
- In the CNE selection with newly formed zones (determined in setting 1 and also used for setting 2), we have an increasing amount of zone-to-zone combinations checked: $|Z| \cdot (|Z| - 1)/2$. The same threshold is used throughout.

The setup of this analysis is summarized in Table 1. Hereby, we can isolate the observed effects. As mentioned above, the nodal pricing solution will serve as a cost-optimal benchmark for all other settings. The difference between setting 1 and setting 2 quantifies which part of the effects are due to newly formed market zones and which part is due to selecting CNEs based on the newly formed market zones. The difference between setting 2 and setting 3 gives an indication regarding the dis-/advantage of selecting market zone-based CNEs versus simply selecting more CNEs in the regular process with different threshold values (α).

Importantly, in all configurations, the flow-based market coupling parameters remain the same. Flow reliability margins (FRM) are set to 0. If we imposed an FRM greater than 0, we would artificially constrain the market outcomes, increasingly so with a growing number of CNEs, as more lines have to reserve this margin before and during market coupling. The used generation shift keys (GSKs) also remain the same throughout the analysis. A flat strategy is used, weighting all nodes in a zone equally (Schönheit et al., 2020a).³ Lastly, no trade is permitted with the adjacent non-FBMC zones.⁴

We assume cost-based redispatch when computing congestion management. Positive redispatch is conducted in ascending order of marginal generation costs (cheapest units first) and negative redispatch in descending order of marginal generation costs (most expensive units first). When reporting congestion management cost, positive redispatch is valued with the additional marginal generation costs and negative redispatch is valued with the saved marginal generation costs (resulting in negative costs). Curtailment is the most expensive option in the model for reducing power output and is assigned a flat cost of 100 EUR/MWh. More details can be found in Schönheit et al. (2020a).

3 Re-configuration of market zones based on clustering

Typically, the re-configuration of new market zones is based on clustering. Chicco et al. (2019) provide an overview of the applied clustering algorithms in this context. They conclude that nodal prices are mostly used as a guide to cluster nodes in order to avoid intra-zonal congestion. Alternatively, PTDFs can also be considered as a metric, in which the variation of nodal PTDFs of the nodes within a zone, relative to a critical network element, are minimized. In the latter approach, the impact of

³ The main reason for this is that newly formed zones may not have conventional power plants anymore. Most GSK strategies, defining how nodes are weighted, take into account information on conventional power plants. The exception is the flat strategy with an equal weighting of all nodes that works for any kind of zone.

⁴ Results in flow-based market coupling are also affected by the adjacent zones that do not participate in the flow-based capacity calculations, e.g. in form of reference flows in the congestion forecast. We want to isolate the effects of selecting CNEs (in setting 1-3) and thus exclude any effects from neighboring zones.

GSKs on market outcomes is implicitly minimized.⁵ Several clustering algorithms in different contexts exist. This paper opts for hierarchical clustering in order to easily include contiguity constraints, i.e. nodes that form a zone need to be physically connected without creating “islands” (visualized below). The latter is an important aspect for electricity to ensure that clustered nodes are physically connected via electrical lines (Chicco et al., 2019). Specifically, we apply a Ward-like hierarchical clustering algorithm including spatial constraints (Chavent et al., 2017). Our model starts from one node per zone and iteratively merges one zone with another until the amount of desired zones is reached. The merging steps happen through minimization of the “merging cost”, which depends on the dissimilarity metric that is adopted.

Two node-specific (nodes $n \in N$) dissimilarity metrics are used for the clustering algorithm, in form of **D0** and **D1**, which are both $|N|$ -by- $|N|$ matrices.⁶

D0: Average nodal prices (“price dissimilarity”): These nodal prices are derived from the nodal pricing approach in the original market zone configuration. Then, mean nodal prices of all hours in the analyzed year are computed and normalized, assuming values between 0 and 1. Thus, 0 means that two nodes have the same average nodal price and 1 is assigned as a dissimilarity between the two nodes with maximum and minimum average nodal prices.

D1: Spatial coherence (“contiguity”): To account for spatial constraints, the adjacency of nodes is taken into account in a binary fashion. Importantly, this is also a *dissimilarity* matrix. Thus, 0 means two nodes are neighbors (connected through a grid line) and 1 means two nodes are not connected directly by a grid line. Note that two nodes that are connected via a third node are valued 1 in this dissimilarity matrix.

The clustering algorithm is provided with both dissimilarity metrics. The relative weighting of contiguity has to be selected (from 0 to 1). When 0 is chosen, only the price dissimilarity is taken into account. This way, the clustering algorithm can combine nodes with very similar average nodal prices. However, the clusters (new market zones) may not be coherent and form “islands”. Conversely, when 1 is chosen, only the spatial coherence (contiguity) is taken into account, disregarding any nodal price information.

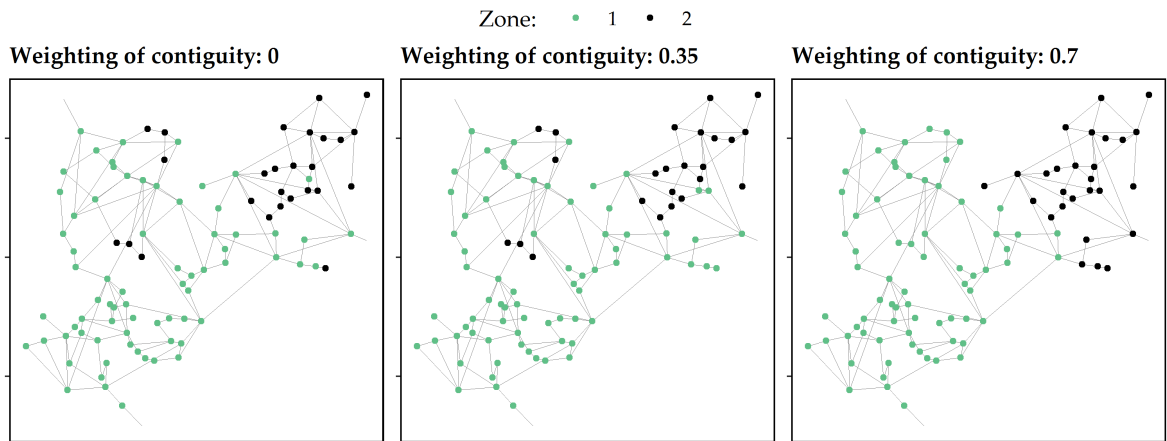


Figure 1: Two new zones formed based on clustering with a weighting of contiguity of 0.0, 0.35 and 0.7.

⁵ A zonal $PTDF_{l,z}^Z$, expressing with what fraction a change in net position of zone z affects the flow on line l , is constituted as a weighted sum of the nodal $PTDF_{l,n}^N$ as follows: $PTDF_{l,z}^Z = \sum_{n \in Z(n)} GSK_{n,z} \cdot PTDF_{l,n}^N$. In the extreme case of equal nodal $PTDF$ s within a zone, it can be seen that $PTDF_{l,z}^Z = PTDF_{l,n}^N$ if $PTDF_{l,n}^N = \text{constant} \quad \forall n \in Z(n)$ since $\sum_{n \in Z(n)} GSK_{n,z} = 1$

⁶ According to Chavent et al. (2017) **D1** “can be a matrix of geographical distances or a matrix build from the contiguity matrix.”

When clustering the grid nodes, for each combination of 1) the relative weighting of contiguity ($y \in \{0, 0.02, 0.04, \dots, 0.98, 1\}$) and 2) the total number of zones ($x \in \{2, 3, 4, 5, 6, 8, 10, 20, 50\}$)⁷, we check if the newly configured zones are coherent. This means we test (after the clustering of each specific configuration, consisting of x, y) if every node is connected to every other node within a new zone, either directly or through connection with neighboring nodes, branching out to all nodes within the new zone. This is exemplified in Figure 1 that shows how two new zones are formed at different levels of weighting the contiguity. The left panel depicts that at a weighting of 0, neither zone is coherent, i.e. there are isolated nodes, disconnected from all other nodes within the same zone ("islands"). With a weighting of 0.35 (middle panel) zone 1 is coherent and zone 2 is incoherent. When choosing a weighting of 0.7, both zones are coherent.

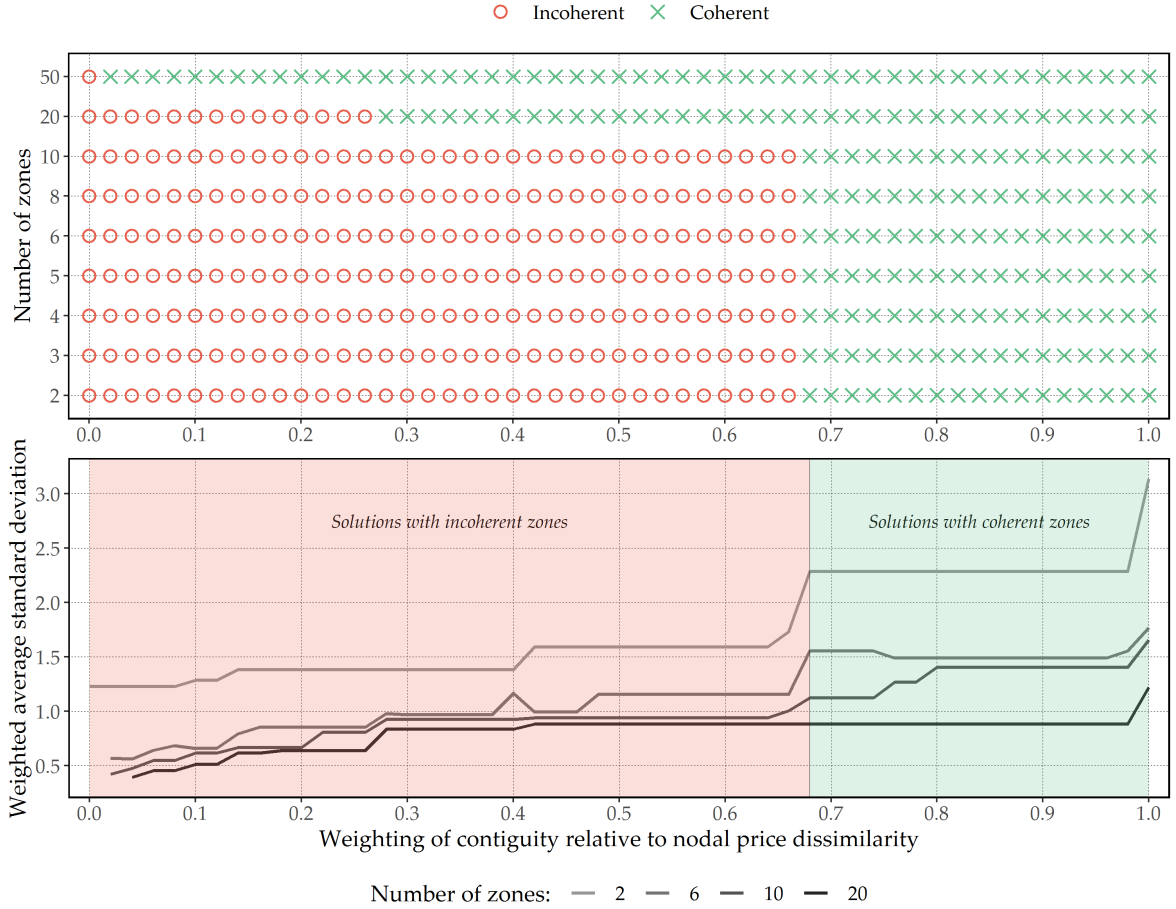


Figure 2: Upper panel: Indication whether or not the weighting of contiguity leads to coherent zones, for different numbers of zones. Lower panel: Average standard deviation of nodal prices (weighted by number of nodes per zone) for different numbers of zones and different weighting of contiguity.

Figure 2 shows if coherent zones are formed, when clustering the nodes with different weightings of the contiguity for different amounts of zones (upper panel). The lower panel shows the average standard deviation of nodal prices within the new zones, *weighted* by the number of nodes per zone to obtain a representative measure for intra-zonal variance of nodal prices that is not skewed by the variance in small zones. As expected, when the spatial constraints (contiguity) are assigned more weight, the newly formed zones (clusters) become coherent. However, the average (weighted) standard deviation of nodal prices rises within the new zones. When many zones are formed (e.g. 20 or 50) a lower weighting of contiguity is needed to form coherent zones. This is not surprising, be-

⁷ The analysis and quantification in Section 4 only include $x \in \{2, 6, 20, 97\}$. Here, we show a greater array of configurations for illustrative purposes. The configuration of 97 zones is not depicted since the one-zone-per-node configuration is always coherent and exhibits no standard deviation in intra-zonal nodal prices.

cause with more zones and fewer nodes per zone it is easier (i.e. more likely) to cluster two or a few connected nodes with similar nodal prices. This task becomes more challenging with a decreasing amount of zones. Ultimately, a weighting of contiguity needs to be chosen so all new zones are coherent, for *all* choices of numbers of zones. Here, we select 0.7 as a weight to ensure the coherence of market zones while minimizing the heterogeneity of nodal prices within the new zones.

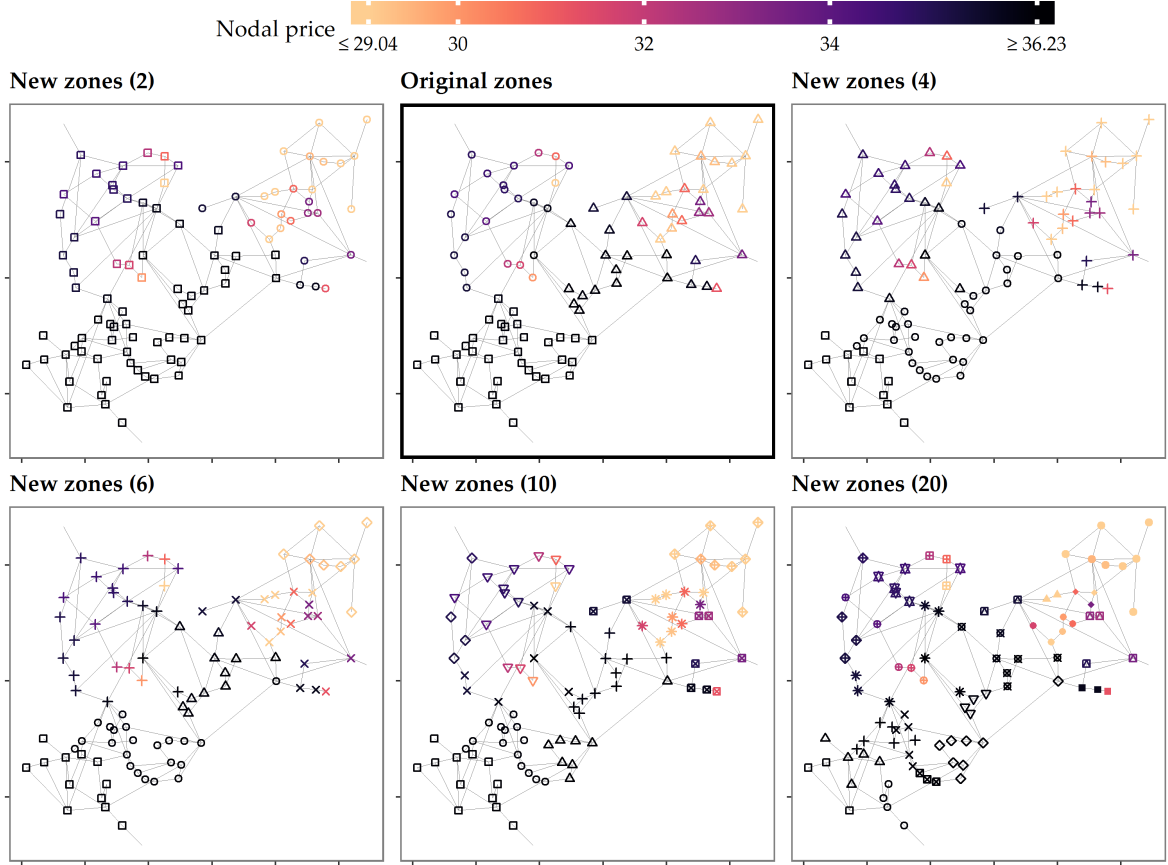


Figure 3: New zones formed based on clustering with a weighting of contiguity of 0.7. The zone affiliation of nodes is indicated by different symbols. Nodal prices are indicated by the color scale, limited to 10th and 90th percentile of nodal price distribution (29.04 and 36.23). Values below or above the percentiles are assigned the same colors as the percentiles.

Figure 3 shows the newly formed zones for 2, 4, 6, 10 and 20 zones. It indicates the average nodal price of each node, from high (dark blue) to low (light yellow). Nodal prices are obtained from a hypothetical nodal market clearing, disregarding the market zone re-configuration. The graphical depiction in both figures confirms that coherent market zones are formed with the weighting choice of 0.7. Figure 3 confirms that average nodal prices become increasingly similar within zones with a higher amount of formed zones: While nodal prices in the upper left panel exhibit vastly different colors, the colors become increasingly similar within zones when the number of zones increases (toward the lower right panel). However, nodal price differences within zones remain mainly due to the spatial constraints, i.e. the requirement of all nodes being connected within a zone.

4 Presentation and discussion of results

In this section, we quantify generation costs for day-ahead market coupling as well as congestion management amounts and costs. This is done according to Table 1, in the following steps, corresponding to the settings.

- Setting 1:** In Section 4.1, we evaluate setting 1, i.e. for the newly configured zones. This is done for 2, 6, 20 and 97 new zones.
- Setting 2:** In Section 4.2, we compute setting 2, by taking the same CNEs as in setting 1 but maintaining the original market zone configuration. Thus, we evaluate the effect of using the same CNEs of the newly formed 2, 6, 20 and 97 zones, in the original 3-zone setting.
- Setting 3:** In Section 4.3, we use setting 3. We remain in the original 3-zone setting and adjust the zone-to-zone PTDF threshold to obtain the same *amount* of CNEs as in the setting of the newly formed 2, 6, 20 and 97 zones. The CNEs, however, differ between setting 3 and setting 1/2 (see explanation in Section 2).

In all settings, we conduct the flow-based market coupling modeling process (base case, market coupling and congestion management) as described in Schönheit et al. (2020a). All results are juxtaposed with the nodal pricing outcome (benchmark) and the regular FBMC process with "standard parameters" (default/original configuration), i.e. original market zones and originally selected CNEs (see leftmost column of Table 1). The base case stays constant over all settings, with the difference of computing one net position per zone (with a changing amount of zones). This way all differences in results among the settings can be traced back to the market zone configuration and CNE selection. Since all problems are linear, the differences in costs (generation costs and congestion management costs) are easily interpretable. However, it should be noted that an addition of non-convexities (e.g., through inclusion of unit commitment constraints or non-convex market clearing and pricing principles) could affect cost differences between a nodal market design and a flow-based coupled zonal market design.

Before detailing the sources of cost differences between setting 1-3 in Section 4.1-4.3, Figure 4 summarizes the results. Displayed are the total annual costs, starting at the default setting with 42 CNEs. For 25, 78, 178 and 265 CNEs, the figure displays the total costs for setting 1 (FBMC with new market zones), setting 2 (3-zone FBMC with market zone-based CNEs) and setting 3 (3-zone FBMC with regular CNEs). For 265 CNEs, also the nodal pricing solution is indicated. Every bar displays the changes in total costs (day-ahead generation plus redispatch/curtailment costs), relative to the default setting.

As further detailed in Section 4.2, much or all of the cost reduction from newly formed market zones (done in setting 1: FBMC with new market zones) can be realized by remaining in the original market zone configuration but maintaining the same CNEs (done in setting 2: 3-zone FBMC with market zone-based CNEs). Simply lowering the threshold to select the same *amount* of CNEs as in setting 1/2 (done in setting 3: 3-zone FBMC with regular CNEs) does *not* have the same effect when low to medium amounts of CNEs are selected (in this analysis, 25-78 CNEs, relative to 265 lines). A very large set of CNEs is necessary to achieve the cost reduction effect from setting 1 and 2 in setting 3. Also, in setting 1 the nodal pricing solution can only be achieved when the number of zones equate to the number of nodes, which is a completely hypothetical case since it is equivalent to implementing nodal pricing.

In what follows, we shed a light on the underlying drivers of these results. We want to point out that this analysis is based on an ideal setting due to the following reasons and simplifications. 1) We use a test network with only three zones in contrast to the much more complex multi-zone FBMC region in reality. 2) We add no extra uncertainty in form of forecast errors in the two modeling steps before the day of delivery, namely the base case (D-2) and market coupling (D-1). The uncertainty in our FBMC setting stems from predictive parameters, specifically the generation shift keys and the selection of critical network elements. 3) We do not allow for trade with the adjacent non-FBMC zones. Due to this ideal setting, we likely underestimate day-ahead generation costs and the need for remedial action as well as overestimate the cost reductions effects of market zone re-configuration and selection of different CNEs. We intend to show the potential benefit of the improved approach to selecting CNEs in a controlled environment. Its performance suggests that it warrants further research.

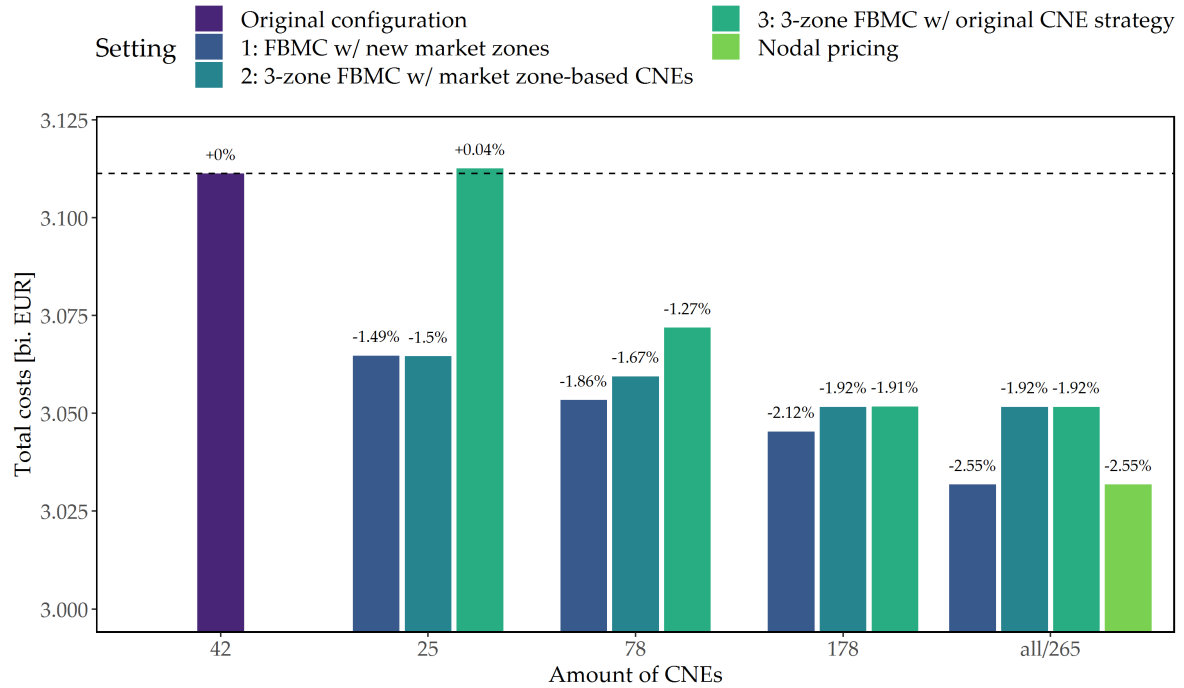


Figure 4: Total costs for various amounts of critical network elements (CNEs) in different settings. Please note that the scale starts at 3 billion EUR.

4.1 Evaluation of re-configured market zones

Figure 5 displays the market coupling generation costs, amounts of congestion management and total costs, for each setting and all configurations. The re-configuration of zones in setting 1 (following the connected squares in Figure 5) leads to a reduction of overall costs, i.e. this effect already comes into force when going from the original configuration to two newly formed zones. This indicates that even fewer but better configured zones (more homogeneous in terms of nodal prices) can lead to cost reductions. With further increases in zones, total costs continuously decrease, generation costs during market coupling increase (but not monotonically) and congestion management amounts decrease.

In accordance with the theory, the nodal pricing approach is the cost minimizing approach. The flow-based market coupling solution converges to this solution. When 97 zones are formed (one for each node within the FBMC area), the flow-based market coupling outcome equates to the nodal pricing solution by definition. In this setup, nodal pricing exhibits no congestion management, or rather, the necessary remedial actions are included in the market coupling solution. This makes the generation costs the most expensive in the nodal pricing approach since the day-ahead dispatch decisions are the most constrained, concretely, the physical constraints of all lines are included (cf. Section 1).

Figure 6 depicts how often what number of price zones are formed during market coupling, for the original setting as well as the newly formed 2, 6 and 20 zones. Additionally, it shows the nodal price distributions, for which every node is assigned the price of the corresponding zone. Evidently, the occurrence of full price convergence (hours during which one price zone forms) decreases with a growing number of re-configured zones. This goes along with the increasing generation costs during market coupling in Figure 5. Interestingly, when 20 market zones are formed, 20 price zones form during 766 hours of the year (rightmost bar in Figure 6). In other words, during almost 9% of the time there is no full price convergence between any of the zones. During many other hours of the year, there are between 13 and 19 price zones when 20 market zones exist. This hints at substantial grid congestions that are signaled to the market and reflected in the price zone formation. The congestion signals are already existent in a less "fragmented" and extreme market zone re-configuration, namely

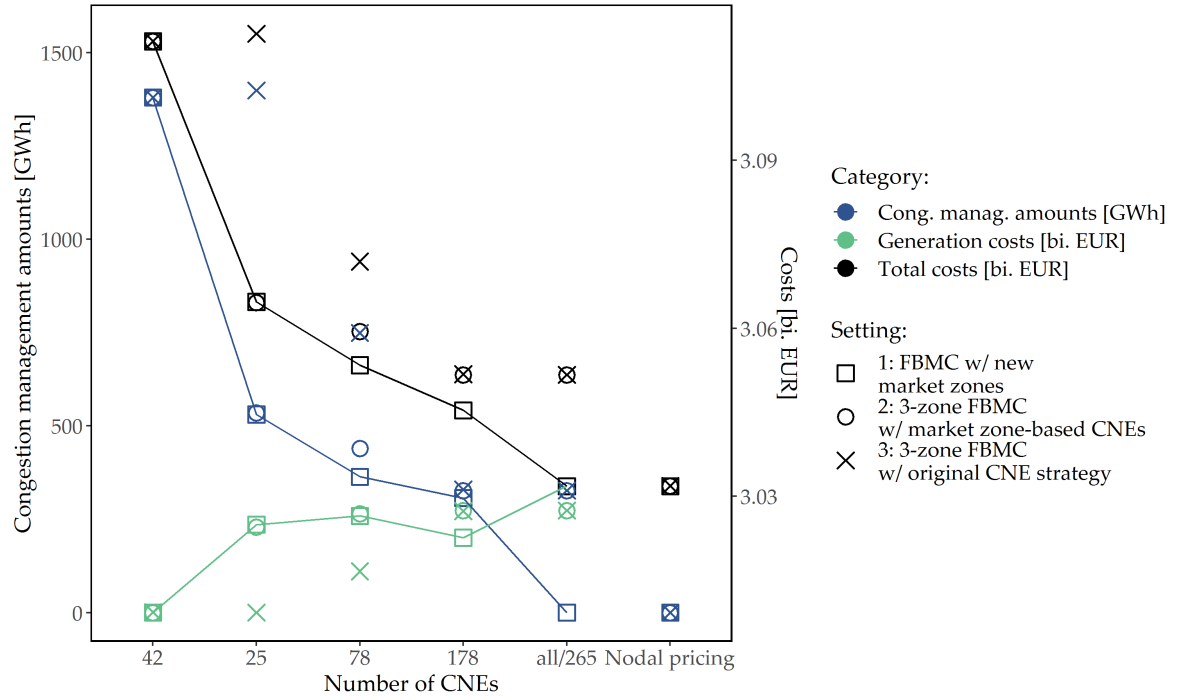


Figure 5: Day-ahead generation costs, congestion management amounts and total costs for setting 1-3. Results are compared with the default (original) configuration (left side, with 42 CNEs) and the benchmark nodal pricing approach (right side).

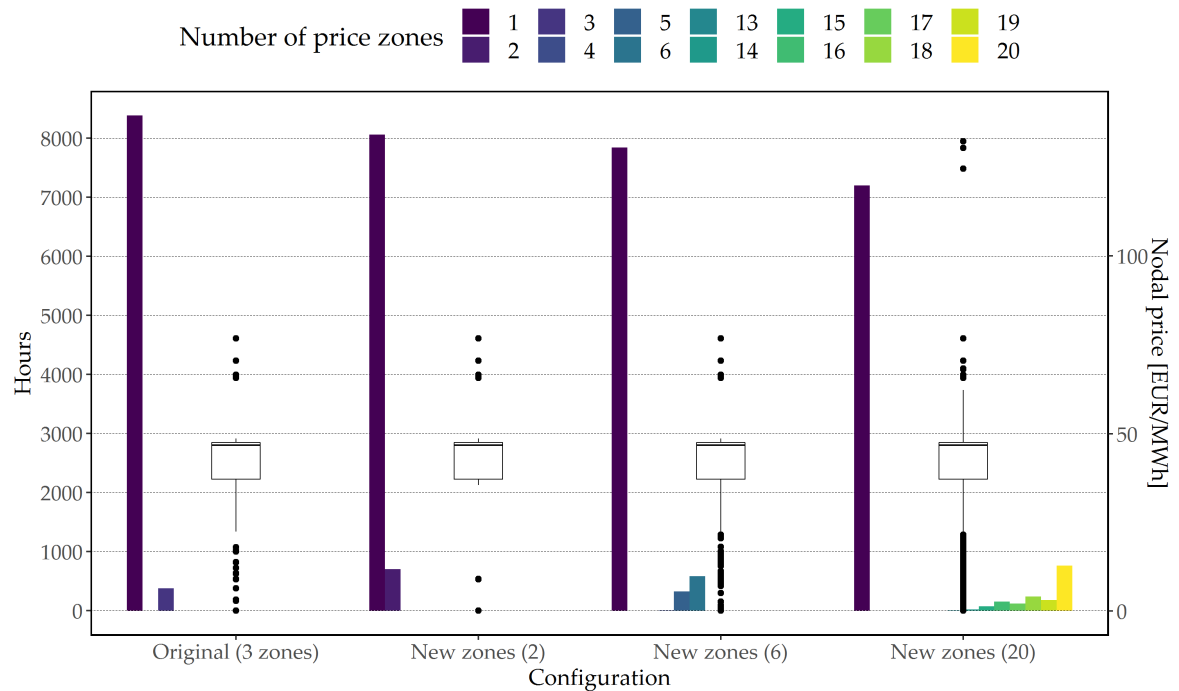


Figure 6: Indication how many hours certain amounts of market zones prevail (bars) as well as distribution of nodal prices during day-ahead market coupling (boxplots).

when six market zones are formed. Here, during 586 hours, six price zones are formed, which is roughly 7% of the hours of the year.

This is confirmed by Figure 7, displaying the “congestion work” on the grid lines. We compute congestion work by quantifying the load on lines that *would* result from an unaltered market dispatch and adding all line flow utilizations that exceed the physical maximum of the lines. This indicates

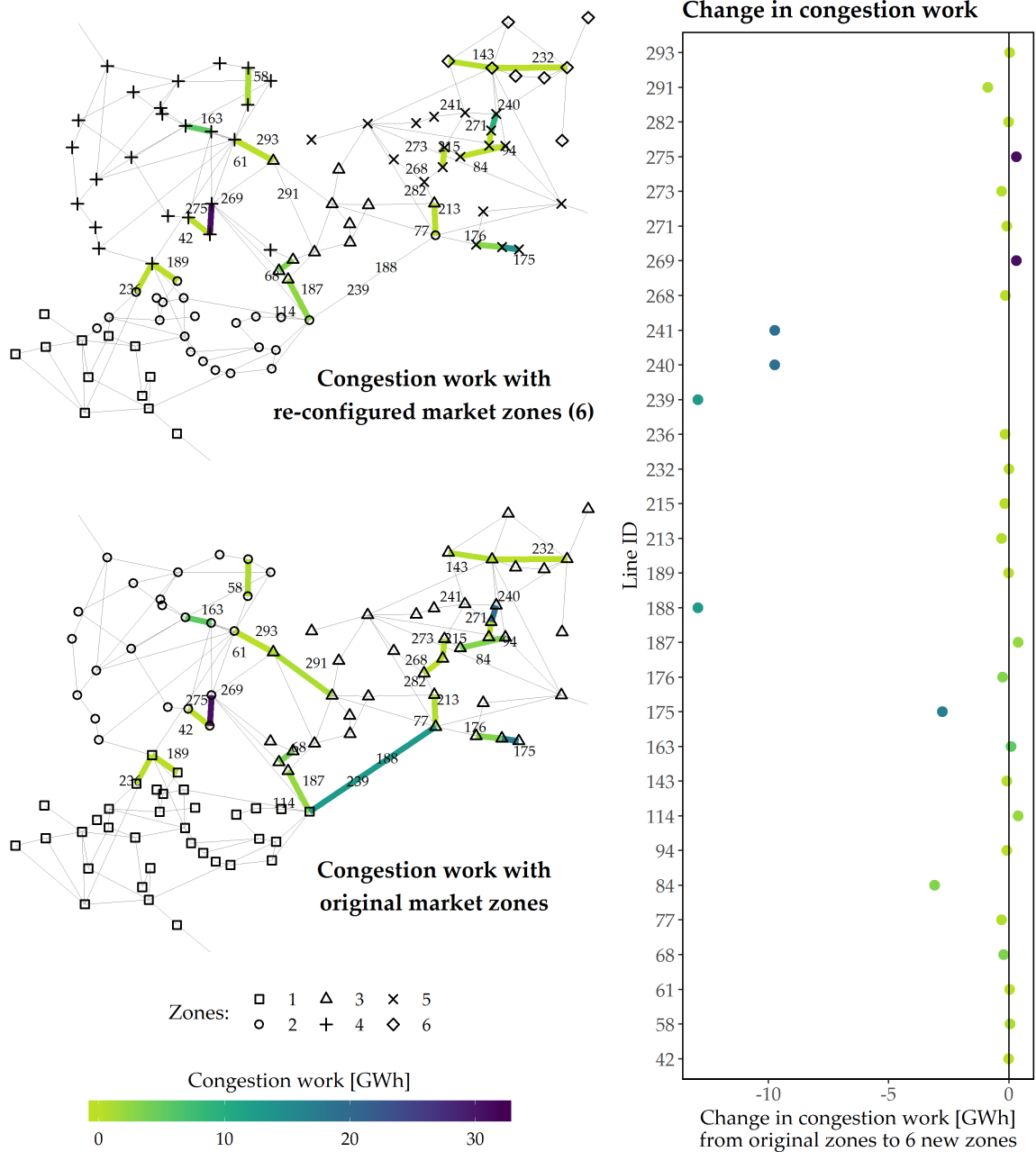


Figure 7: Left: Annual line-specific congestion work with line flows resulting from day-ahead market coupling before congestion management. Right: Change in congestion work when changing from original zones to the 6 new zones. Colors of the dots correspond to congestion work in the original setting.

the amount of congestion work necessary for each line. The depiction confirms that the re-configured six market zones result in lower amounts of congestion work on some lines and completely avoided congestion work on other lines. The right side of Figure 7 confirms that some lines that are congested to a large degree in the original setting, require less or no congestion work in the newly configured six zones. For example, the interconnection lines between zone 1 and 3, lines 188 and 239, are congested in the original configuration, but relieved from congestion in the new configuration, as they become intra-zonal CNEs. However, many other lines, mostly with lower levels of congestion work, exhibit similar levels in both configurations.

From a perspective of minimizing total costs, more market zones are advantageous and a way of closing the gap to an optimal nodal pricing solution. As argued in Section 2, a growing number of market zones goes along with a growing number of critical network elements that are moni-

tored. Hence, the question emerges, if the observed cost-reducing effects are mostly due to the newly formed zones or mostly due to the different and greater selection of critical network elements.

4.2 Evaluation of original market zones with market zone-based critical network elements

In this section, setting 2 is evaluated. We use the CNE selection from the previous setting 1 but return to the original market zone configuration. This is an interesting evaluation since, politically, market zone reconfiguration is a controversial topic. However, CNE selection strategies are at the discretion of TSOs. Hence, implementing an improved selection of CNEs from market zones re-configuration is much more feasible.

Figure 5 displays the results (indicated by circles). As described in Section 2, the number of CNEs correspond to the re-configured market zones, i.e. 25, 78 and 178 come from the newly formed 2, 6 and 20 zones. We run the model for an additional configuration with all lines considered critical ("all/265"). One can observe similar cost reductions as in the previous section (setting 1), concretely the squares and circles in Figure 5 are close together. Notably, for 78 and 178 re-configured market zone-derived CNEs, around 90% of cost savings (from 2, 6 and 20 re-configured zones, respectively) can be maintained, even in the original market zone setting. In the case of using the 25 CNEs from setting 1 (when 2 zones are formed), the same cost reductions can be achieved in the original market zone configuration. However, costs with 178 and 265 CNEs exhibit no difference in setting 2. Hence, there is a *limit to the cost-reducing potential of the proposed CNE selection strategy within the original market zone setting*. While re-configured zones can eventually reach the benchmark costs of a nodal pricing approach (with an equal number of zones and nodes), this convergence cannot be achieved within a flow-based market coupling setting with multi-node zones.

Thus, in the setting of this analysis, much of the cost reduction is achieved by selecting CNEs based on the re-configured market zones. In most cases, the actualization of re-configuring the zones leads to small additional cost reduction, i.e. the difference between setting 1 and 2. With market zone re-configuration, we not only choose *more* but also *different* CNEs than in the regular CNE selection. The market zone-derived CNEs include many cross-border lines between the new zones as well as lines strongly affected by trade between the new zones.

Therefore, the questions arises, whether we can achieve these same observed cost reduction effects by simply selecting more CNEs in the original market zone setting with the regular selection process, without the estimation of new market zones. This is achieved by reducing the threshold level for the zone-to-zone PTDF values, as described in Section 2.

4.3 Evaluation of original market zones with increasing critical network elements based on regular selection procedure

In this section we evaluate setting 3. We match the *amount* of CNEs used for setting 1 and 2, namely 25, 78, 178 and 265/all, by adjusting the selection threshold level (α) to 14%, 4.65%, 2.05% and 0%, respectively. Figure 5 displays the results (indicated by X's).

Especially for *low to medium* amounts of CNEs, the cost-reduction effects are *not* achieved (large difference between X's and squares in Figure 5). In fact, when 25 CNEs are selected, the total costs increase, compared to the default case with the original CNE selection. The costs reach similar levels to setting 1 and 2, only when 178 or 265 CNEs are selected. When selecting such large amounts of CNEs, e.g. 178, the chances are large to have similar sets of CNEs in setting 3 compared to setting 1/2. In fact, 135 of the 178 CNEs (ca. 76% overlap) are selected in both settings, i.e. with the CNE selection based on 20 re-configured zones and with the regular CNE selection process and a threshold value of 2.05%. In comparison, for 2 zones (25 CNEs), the common CNEs are only eleven (44% overlap) and for 6 zones (78 CNEs), the common CNEs are 56 (ca. 72% overlap). Hence, with very large sets of CNEs, cost reduction effects can be achieved in the regular FBMC setting, similar to setting 1 and 2. Importantly, with low (and more realistic) amounts of CNEs (25 in this analysis), this is not possible.

As expected, the results of 78 CNEs in setting 3 are closer to the results of setting 1/2 (e.g. compared to choosing 25 CNEs), as the overlap of CNEs is also quite large. However, it appears that certain important CNEs are not included in the regular CNE selection process, leading to lower market coupling costs but larger congestion management volumes that more than offset the savings during trade.

5 Conclusion and implications

Flow-based market coupling captures the utilization of grid elements and takes into account how the grid utilization is affected by trade. If FBMC captured grid utilization and nodal information perfectly, we would not need new market zones. However, the algorithm of FBMC relies on many predictive parameters, such as congestion forecasts and generation shift keys, to render possible the incorporation of nodal information during a zonal market coupling. Therefore, the congestion signals sent to the market are *imperfect* within flow-based market coupling, resulting in additional costs compared to the nodal pricing solution. We show that re-configured market zones decrease the within-zone (hypothetical) nodal price levels and reduce the need for congestion management, which leads to FBMC results converging to the nodal pricing solution. However, re-defining market zones is a topic with many regulatory and political hurdles. Importantly, this analysis suggests that *much of the cost-reducing effect of newly formed market zones can be retained by selecting critical network elements based on these particular re-configured market zones, even in the absence of realizing the re-configuration itself.*

This has important ramifications for the methodology of flow-based market coupling. Our results strongly suggest that the CNE selection process needs to be much more congestion-oriented, rather than relying on static criteria, such as the zone-to-zone PTDF values. In a regular market zone setting, such as the three zones in this analysis, zone-to-zone PTDF values strongly depend on the chosen generation shift key. This is especially true with large zones, because the effect of trade on the grid utilization is spread across many internal lines and the detection of intra-zonal congestion vastly depends on where generation is expected to come from (the assumption a GSK makes) (Schönheit et al., 2020a). If the GSK is chosen incorrectly, or if the underlying assumption is very weak, e.g. equally weighting all nodes in a zone, which is what we (have to) do in this analysis due to the described reasons, the CNE selection process may have major flaws. In contrast, selecting CNEs based on re-configured market zones has the advantage of including all lines that cross borders in the setting of new zones. These are likely highly utilized intra-zonal lines in the original market zone setting, since the congestion is the reason for creating new zones at these points in the grid. Further, with more market zones, zones are smaller and evaluating zone-to-zone PTDF values more likely nominates lines as CNEs that are affected by trade in the case of new market zones. This, in turn, benefits the consideration of trade in the original market zone configuration, because basing CNEs on new market zones enforces to consider elements between nodes with heterogeneous nodal prices.

Despite making simplifying assumptions and using a test network, this analysis provides helpful insights regarding the selection process for critical network elements. We find strong evidence that a congestion-based process helps to reduce overall costs and the need for congestion management. Considering more optimal market zones, i.e. clustering nodes with similar nodal prices, can constitute a helpful foundation for this selection process. This is a departure from the current process, based on static grid characteristics and thresholds. Transmission system operators, regulators and researchers could utilize (nodal price-based) clustering algorithms to find optimal market zones, helping to better identify CNEs, as opposed to purely basing the selection process on zone-to-zone PTDFs and thus only relying on GSKs to introduce nodal signals, and thereby congestion signals, into the methodology. The re-configuration process helps to include otherwise neglected price information. This helps to allocate and anticipate congestions because of the price-dependent order of dispatch.

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