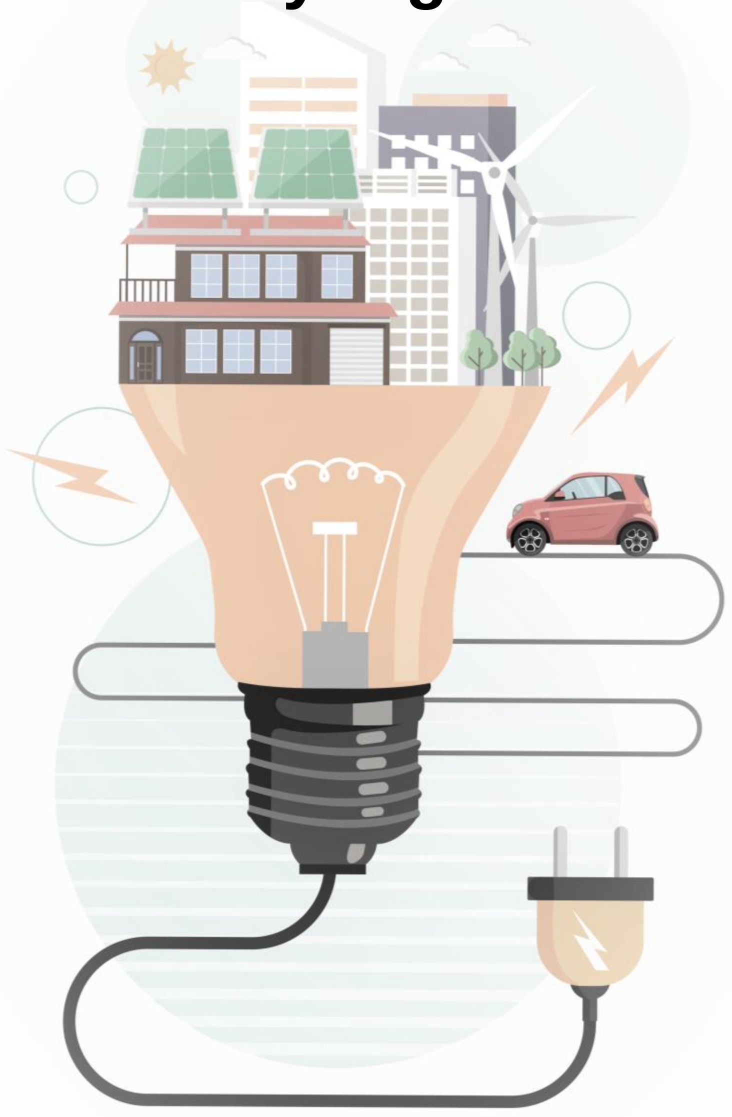
European Commission

ASSET Study on

Congestion cost allocation in the framework of Art.16(13) of the electricity regulation



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About the ASSET project

The ASSET Project (Advanced System Studies for Energy Transition) aims at providing studies in support to EU policy making, research and innovation in the field of energy. Studies are in general focussed on the large-scale integration of renewable energy sources in the EU electricity system and consider, in particular, aspects related to consumer choices, demand-response, energy efficiency, smart meters and grids, storage, RES technologies, etc. Furthermore, connections between the electricity grid and other networks (gas, heating and cooling) as well as synergies between these networks are assessed.

The ASSET studies not only summarize the state-of-the-art in these domains, but also comprise detailed qualitative and quantitative analyses on the basis of recognized techniques in view of offering insights from a technology, policy (regulation, market design) and business point of view.

Disclaimer

Authors

This study has been developed as part of the ASSET project by Tractebel Impact.

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Executive summary

Context of the study:

Congestion management costs due to network congestion represent a non-negligible part of the total system cost of the Core capacity calculation region. Currently, the congestion management cost is carried by the zone in which the congestion occurs. However, congestions may not only be due to internal exchanges but also to loop flows or cross-zonal exchanges. The congestion cost should thus be shared between those responsible of the congestion. The need of defining a methodology for congestion cost allocation was clearly identified by the different stakeholders (ACER, TSOs and European Commission), and a proposition of methodology was made in February 2019 [2].

The state of the current methodology

The cost sharing methodology is composed of four steps :

- **Flow decomposition**: the flow on the congested network elements, for which remedial actions have been activated, are decomposed into flow shares of different flow types;
- **Transformation**: the flow shares are transformed into bidding zone shares;
- **Mapping**: the costs of optimized remedial actions are assigned to all the congested network elements for which these remedial actions have been activated;
- **Multiplication**: the outcome of the mapping and the transformation steps are combined and aggregated to a final cost per bidding zone.

This report assesses the performances of the five different mapping methodologies that were envisaged throughout the development of the congestion cost allocation methodology:

- **Volume based mapping (VBM)**: allocation based on the global relieve of the congestion after all the remedial actions;
- **Improved volume based mapping (IVBM)**: allocation based on the global relieve of the congestion after all remedial actions (as the VBM) and on the individual relieve of each congestion after each remedial action;
- **Shadow price based mapping (SBM)**: allocation based on the shadow price of the line constraints;
- **Individual optimisation based mapping (IOBM)**: allocation proportionally to the cost of solving each congestion alone;
- **Restricted individual optimisation based mapping (RIOBM)**: allocation proportionally to the cost of solving each congestion alone based only on linear combinations of the actual remedial actions (i.e. redispatch and PST actions). This methodology is called "Least Cost Based Mapping" (LCBM) in the ACER decision on the common methodology for redispatching and countertrading for the Core CCR [3].

Assessment of the mapping methodologies

This report applies the complete methodology for congestion management costs allocation to a test system to assess the performance of the different mapping methodologies. The evaluation criteria used are the following:

- **Fairness**
- **Incentive compatibility**
- **Practicality**

The fairness is evaluated based on the distance between the zonal socio-economic welfare repartition for the different methodologies compared to the nodal reference. Based on the global aggregated results (i.e. annual congestion cost per zone), no fundamental differences between the different mapping methodologies is found. **The repartition of the socio-economic welfare is thus similar between the different mapping methodologies.** However, hourly congestion cost allocation could vary significantly between the different mapping methodologies.

This report highlights possible perverse incentives thanks to study cases on the toy model. For example, in specific situations, the increase of the internal transfer capacity of a zone could lead to an increase of the redispatch cost allocated to this zone, or specific non-optimal PST settings in the initial Common Grid Model could lead to a decrease of the zone operating the PST. However, the possibility of having **perverse incentives is independent of the mapping methodologies**. Note that these perverse incentives are shown for very specific cases, and it does not imply that they will be important in reality. Nevertheless, only a high transparency of the TSOs in the capacity calculation process can ensure that the possible adverse consequences of these perverse incentives will not become a reality.

The practicality of the different mapping methodologies is assessed based on the application of the methodologies on the example. The practicality can be described as the "Clarity" of the method and "Easiness to compute". Strong differences regarding these criteria are highlighted. According to the consultant**, it is essential to adopt a methodology that is clear and transparent and has an acceptable calculation time**. These criteria should be even more decisive since the results of the different methodologies are relatively similar.

<u>Conclusions and recommendations</u>
Table 1 presents a summary of the assessment of the different methodologies.

<table>
<tr><th rowspan="2">Methodology</th><th rowspan="2">Fairness</th><th rowspan="2">Incentive compatibility</th><th colspan="2">Practicality</th></tr>
<tr><th>Clarity</th><th>Easiness to compute</th></tr>
<tr><td>VBM</td><td>- No linking of specific congestions to specific RAs</td><td rowspan="3">Possibility of perverse incentives independent of the mapping methodology</td><td>+ Only global utility</td><td>+ No additional LF or optimisation</td></tr>
<tr><td>iVBM</td><td rowspan="2">No significative difference between the mapping methodologies</td><td>= Global and individual utility
- Dependent on the slack node
- Possibility of negative values</td><td>= Additional LF for each RA</td></tr>
<tr><td>SBM</td><td>- Based on shadow price through a complex iteration loop process[1]
- Possibility of binding constraints not part of the initially overloaded elements</td><td>- Remedial optimisation loop</td></tr>
</table>

[1] The SBM methodology requires to compute the shadow prices of the congested elements throughout an iteration loop that increases the thermal limit of the binding constraints by a specific but small quantity per step until there is no more remedial actions applied. This methodology is complex and may lack of clarity

IOBM			- Possibility of negative values → complex post processing - Need of fallback procedure in particular cases	- Remedial optimisation for each congestion - High computation time - Application of non-costly RAs can be significantly different in individual and global optimization
RIOBM			- Possibility of negative values → complex post processing	- Remedial optimisation for each congestion - Application of non-costly RAs can be significantly different in individual and global optimization

Table 1: Assessment of the mapping methodologies.

In conclusion, the assessment reveals that future work on mapping methodologies should primarily focus on the practicality of the solution. Considerations around fairness and incentive compatibility seem to be less reliant on the methodology applied.

Finally, this report shows that some methodologies (i.e. iVBM, SBM and IOBM) are not defined in an exhaustive manner in public documents, which leaves room for interpretation in any practical implementation. Such gaps could hamper the transparency of the allocation process and should thus be addressed.

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Acronyms

XNE	*cross-border relevant network element* network element identified as cross-border relevant and on which operational security violations need to be managed in a coordinated way
XNEC	*cross-border relevant network element with contingency* XNE associated with a contingency (N-1 situation). In this report, the term XNEC gathers as well the cross-border relevant network element in N-0 situation.
PST	*Phase-shifting transformer*
RA	*Remedial action*
BZ	*Bidding zone*
CCR	*Capacity Calculation Region*
CACM	*Capacity Allocation & Congestion Management*
VBM	*Volume Based Mapping*
iVBM	*Improved Volume Based Mapping*
SBM	*Shadow Price Based Mapping*
IOBM	*Individual Optimisation Based Mapping*
RIOBM	*Restricted Individual Optimisation Based Mapping*
LCBM	*Least Cost Based Mapping*

1 Introduction

Because the European electricity market relies on a zonal approach, the outcome of the market clearing may result in power flows over transmission elements[2] exceeding the thermal capacities of these elements. In order to alleviate these overloads, remedial actions must be taken. Remedial actions can be non-costly, such as the use of phase-shifting transformers and topological actions, or costly, such as redispatching and countertrading. **Redispatching** is defined in Article 2(26) of the Regulation (EU) 2019/943 as "*a measure, including curtailment, that is activated by one or more transmission system operators or distribution system operators by altering the generation, load pattern, or both, in order to change physical flows in the electricity system and relieve a physical congestion or otherwise ensure system security*". It has to be noticed that this definition of "Redispatching" therefore also includes countertrading cost. Indeed, **countertrading** is defined in Article 2(27) of Regulation (EU) 2019/943 as "*a cross-zonal exchange initiated by system operators between two bidding zones to relieve physical congestion*". To simplify the discussion, the remainder of this report refers to "congestion management costs", including costs for both redispatching and countertrading.

These remedial actions lead to an additional cost for the system. Already today, congestion management costs represent a non-negligible part of the total system cost. Indeed the redispatch cost in Germany, for example, amounted to 930 M€ in 2019 and 1075 M€ in 2018[3]. It is expected that the further development of intermittent renewable energy sources as well as the imposition of a minimum threshold of 70 percent of cross-zonal capacity (Article 16(8) of the Regulation (EU) 2019/943) available for trade will tend to increase the occurrence of network congestion and thus the congestion cost.

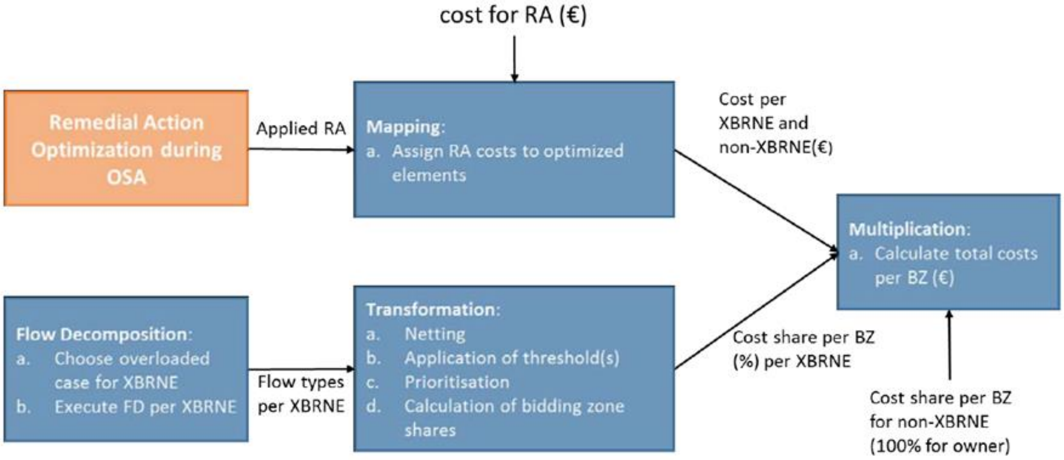
Currently, the congestion management cost is carried by the electricity consumers of the zone in which the congestion occurs. However, congestion may not only be due to internal exchanges but also to loop flows or cross-zonal exchanges. The congestion cost should thus be shared between those responsible for the congestion. In that framework, Article 16(13) of Regulation (EU) 2019/943 states that: "*When allocating costs of remedial actions between transmission system operators, regulatory authorities shall analyse to what extent flows resulting from transactions internal to bidding zones contribute to the congestion between two bidding zones observed, and allocate the costs based on the contribution to the congestion to the transmission system operators of the bidding zones creating such flows except for costs induced by flows resulting from transactions internal to bidding zones that are below the level that could be expected without structural congestion in a bidding zone. That level shall be jointly analysed and defined by all transmission system operators in a capacity calculation region for each individual bidding zone border, and shall be subject to the approval of all regulatory authorities in the capacity calculation region*".

If the need to define a methodology for congestion management cost sharing is reaffirmed in Regulation (EU) 2019/943, it must be emphasized that the need was already identified in article 74 of Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (called CACM). It states that the methodology to allocate the congestion cost among TSOs has to be defined commonly by the TSOs of a Capacity Calculation Region (CCR). Although several CCRs defined already methodologies to comply with article 74 of CACM, the ones in place rely on simple sharing keys (e.g. 50-50) without trying to allocate the costs based on the actual contributions to the congestions. Only the Core CCR is developing a methodology to consider the actual contributions to the congestions in the way to share the cost of remedial actions. As illustrated in Figure 1, in the proposal from the Core CCR published in February 2019 [2], the cost sharing methodology is composed of several steps:

[2] Transmission lines and transformers (including phase-shifting transformers).

[3] Source : ENTSO-E, "*Transparency Platform – Cost of Congestion Management*", [Online]. Available: https://transparency.entsoe.eu/dashboard/show (consulted in October 2020).

- **Flow decomposition**: the flow on the congested network elements, for which remedial actions have been activated, shall be decomposed into flow shares of different flow types;
- **Transformation**: the flow shares shall be transformed into bidding zone shares;
- **Mapping**: the costs of optimized remedial actions shall be assigned to all the congested network elements for which these remedial actions have been activated;
- **Multiplication**: the outcome of the mapping and the transformation steps shall be combined and aggregated to a final cost per bidding zone.



Source: [2]

Figure 1: Overview on cost sharing calculation.

Until November 2020, no agreement within the Core CCR was found regarding the methodology to be used. It should be noted that this lack of methodology also resulted in many TSOs requesting a derogation from the minimum level of capacity to be made available for cross-zonal trade of 70 percent (e.g. [5], [6], [7], [8]).

In November 2020, the decision of ACER on the common methodology for redispatching and countertrading for the Core CCR was published ([3]). The methodology selected for the mapping is the one called Least-Cost Based Mapping (LCBM) in the decision of ACER and called Restricted Individual Optimisation Based Mapping (RIOBM) in this report.
Nevertheless, the different stakeholders (ACER, TSOs and European Commission) seem to be converging currently towards a methodology. In particular, the "Mapping" stage has been at the core of the latest discussions. **Therefore, this report focuses on the performances (quantitative and qualitative) of the different mapping methodologies that are being envisaged in the congestion management cost allocation methodology of Core CCR**. The report is structured as follows:

- Chapter 1 of this report illustrates the congestion cost allocation methodologies introduced here above in a comprehensive manner by applying them to a toy model; Chapter 2 proposes, a preliminary assessment of the mapping methodologies according to several evaluation criteria;
- Chapter 3, performs a detailed assessment of the mapping methodologies, based on a test system application;
- The report concludes with a critical discussion of the mapping methodologies and provides suggestions for the further development of the Core CCR congestion management cost allocation methodology, with a focus on the mapping stage.

2 Presentation of allocation methodologies

This first chapter presents in detail the current state of the Core CCR methodology to allocate the congestion management cost. As mentioned in the introduction, the methodology consists of four main steps :

1. Flow decomposition;
2. Transformation;
3. Mapping;
4. Multiplication.

The methodology of each step is presented theoretically and is then applied to a toy model. It has to be noted that the methodologies are presented only based on the documents made available by the European Commission and ACER or publicly available ([1], [2]). The modification or additions concerning the methodology that were done in order to apply the methodology to the test system will be mentioned in the following chapter.

2.1 Toy model application

The toy model consists of a system with 2 bidding zones, 4 nodes, 4 lines, 3 generators and 2 loads. See Figure 2. Nodes 1 and 3 are locations with relatively cheap generation, but without any load. Load is located in Nodes 2 and 4, but generation in these nodes is relatively expensive, such that imports from Nodes 1 and 3 are expected. However, transmission lines are characterized by thermal capacity limits (F^{max}) and reactance (X).

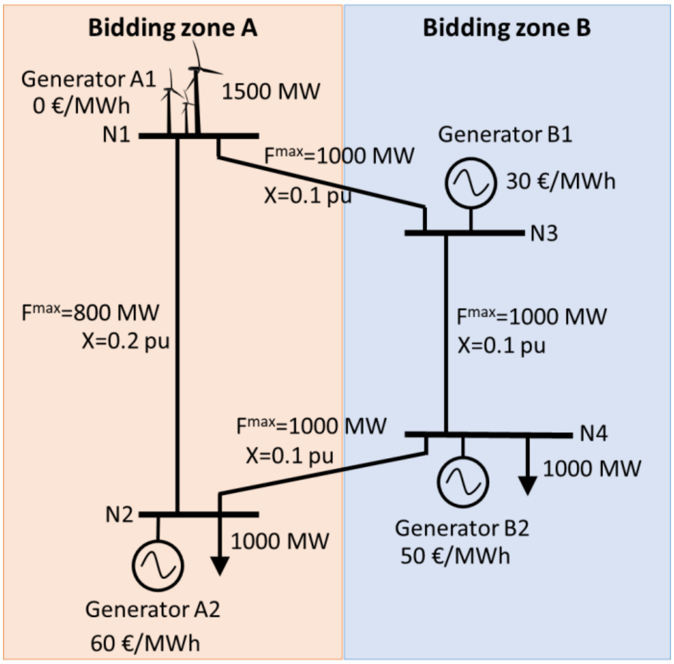


Figure 2: Representation of the toy model.

Market clearing and congestion management

First, the solution of the Flow-Based Market Coupling (FBMC) is computed, followed by the solution after redispatch. The approach used is inspired by [4]. Note that, in order to simplify the analysis, N-1 security constraints are not enforced here[4].

The solution is presented in Figure 3.

[4] Consequently, the power flows on a transmission element must be below its thermal limit only for the normal (N-0) state.

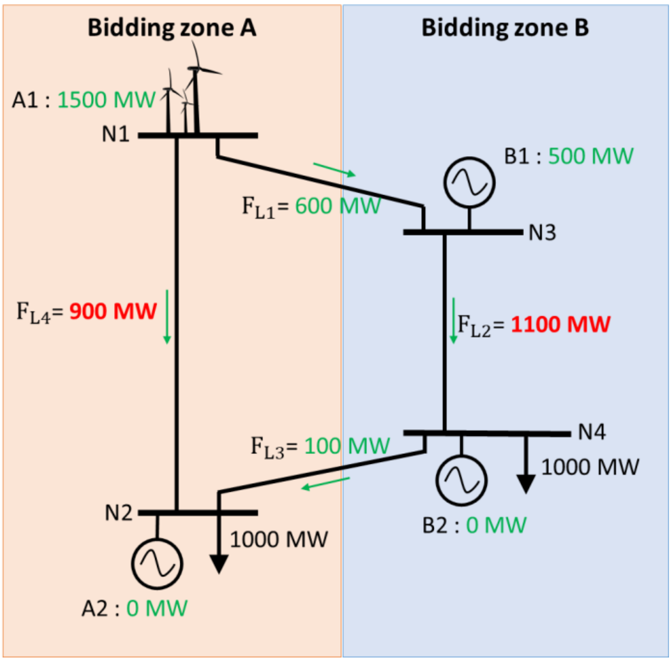


Figure 3: Solution of the FBMC of the toy model.

Comparing with Figure 2, it can be noticed that the lines L2 and L4 are congested. This requires congestion management measures by the TSOs after the market clearing.

The redispatch is computed considering a cost compensation for upward and downward redispatch, with full cooperation of the TSOs. The solution is presented in Figure 4.

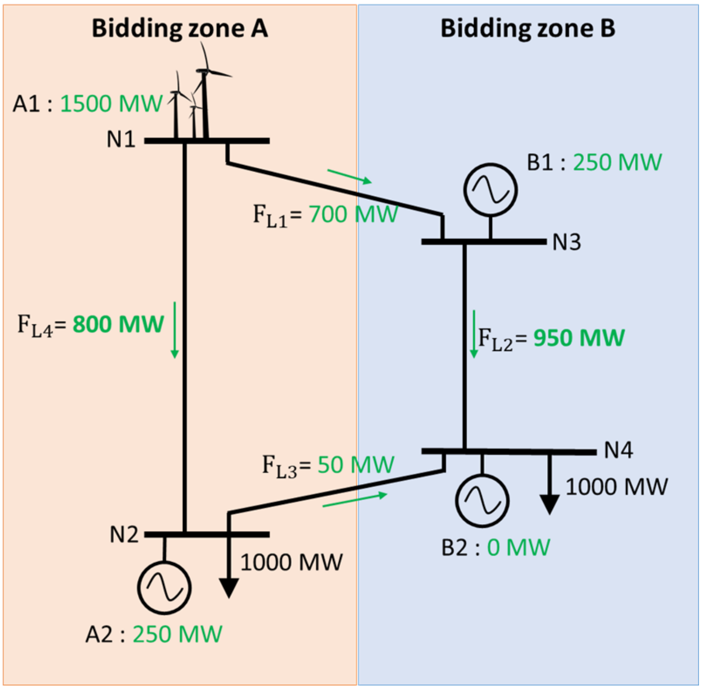


Figure 4: Solution after redispatch of the toy model.

The variation of the output of the generators and the corresponding cost is presented in Table 2.

Generator	FBMC	After redispatch	Redispatch cost
A1	1500 MW	1500 MW	0 €/h
A2	0 MW	250 MW	15000 €/h
B1	500 MW	250 MW	-7500 €/h
B2	0 MW	0 MW	0 €/h
Total	2000 MW	2000 MW	**7500** €/h

Table 2: Variation of the output of the generators, toy model.

The total congestion management cost in this example is thus 7500€/h. This cost will be allocated among the two bidding zones throughout the following sections in order to illustrate the methodology.

2.2 Flow decomposition – the Power Flow Colouring method

2.2.1 Methodology

The aim of this step is to decompose the flow of congested elements into flow types. The different flow types are :

- Loop flows
- Internal flows
- Transit flows
- Import/Export flows
- Phase shifter flows

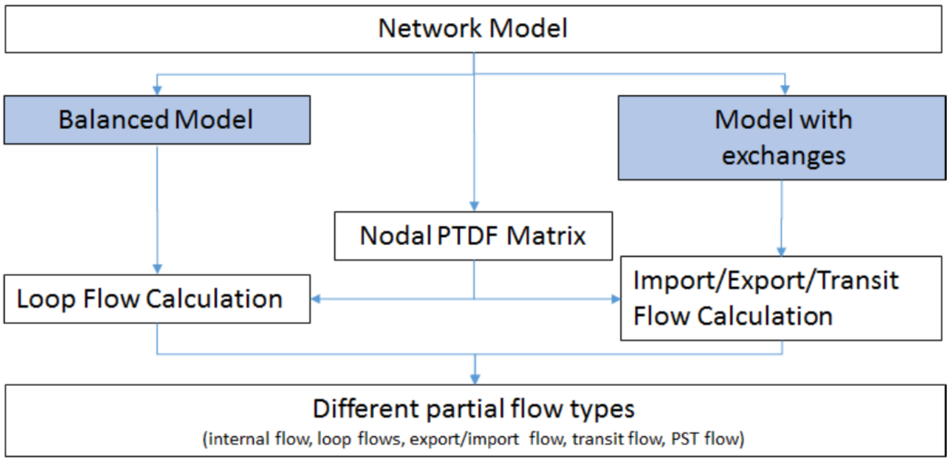
Several methods were first considered by Core TSOs for the flow decomposition :

- Power Flow Colouring
- Full Line Decomposition
- Multi-stage Full Line Decomposition

However, since the methodology retained within Core CCR is the Power Flow Colouring (PFC) methodology, the remainder of the study considers thus only this methodology.

The PFC methodology aims at splitting the flows originating from the market coupling process ("Allocated flows", also called here "Exchange flows", consisting of "Transit flows" and "Export/import flows"), the internal flows and loop flows.

The process of the PFC methodology is illustrated in Figure 5.



Source: [2]

Figure 5: Representation of the process of the PFC methodology.

The solution is decomposed into a "Balanced model" without commerical exchanges and a "Model with exchanges" with commercial energy exchanges only. The "Loop flows" and "Internal flows" are obtained using the "Balanced model" and the "Exchanges flows" using the "Model with exchanges".

Balanced model

The area balancing is performed according to the predefined Generation Shift Keys (GSKs) and Load Shift Keys (LSKs). In the initial proposal of the Core TSOs [2], for the exporting areas, the generator outputs are lowered based on the GSKs, while, for the import areas, the loads are lowered based on the LSKs. However, the corresponding ACER decision [3] does not explicitly discriminate anymore exporting and import areas: the import areas can be balanced by using the same GSKs/LSKs principles as for the exporting areas.

Model with exchanges

The nodal injections are obtained as the difference between the nodal injections of the initial model and the nodal injections of the "Balanced model".

The particular generator-load exchanges can be determined by applying one of the two following approaches :

- *Net position approach without consideration of geographical proximity:* Each remaining generation (nodal generation in the "model with exchanges") feeds in each remaining load (nodal load in the "model with exchanges") proportionally to all the remaining loads in the network.
- *Net position approach with consideration of geographical proximity (perfect-mixers):* Each exporting zone feeds in each importing zone by considering the distance among them over a perfect-mixer approach.

However, the ACER decision [3] does not request to separate allocated flows per originating BZs (see section 2.3.1), which means that it is then not necessary to compute the generator-load exchanges.

2.2.2 Toy model application

The "Balanced model" and "Model with exchanges" are presented in Figure 6 and Figure 7.

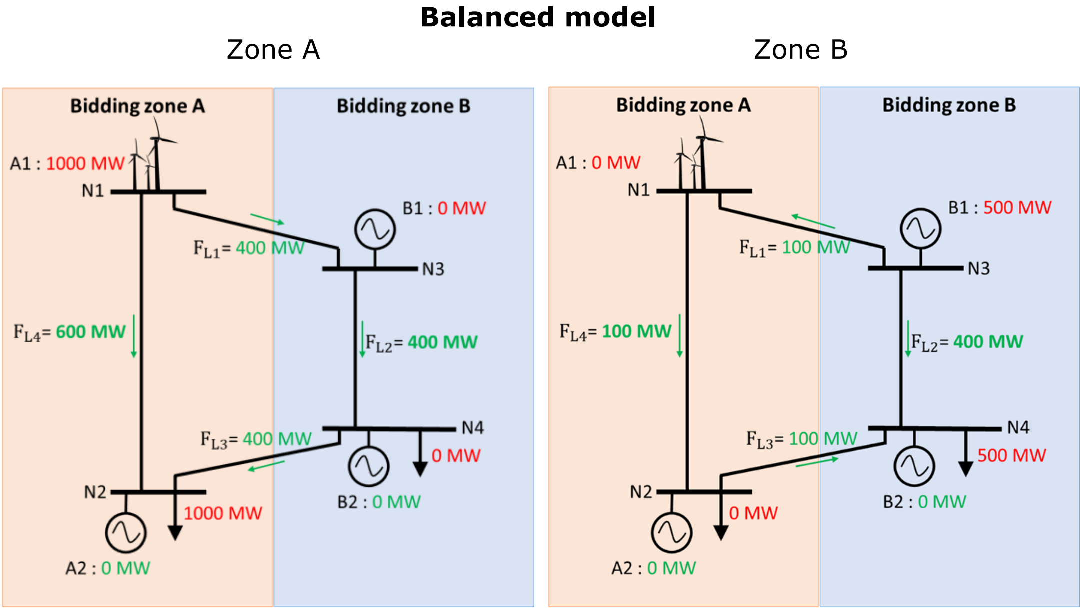


Figure 6: Balanced model of the toy model.

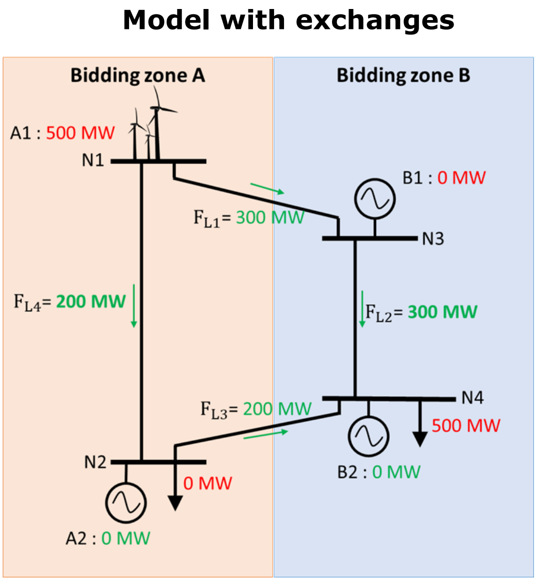


Figure 7: Model with exchanges of the toy model.

Based on the flow decomposition presented here above, the flow on the lines L2 and L4 can be decomposed as:

	L2 [MW]	L4 [MW]
Internal flows	400	600
Loop flows	400	100
Export/Import	300	200

Table 3: Flow decomposition, toy model.

2.3 Transformation

2.3.1 Methodology

The aim of this step is to process the flow shares of the flow decomposition to obtain bidding zone shares.

This step is subdivided in five sub-steps:

- Netting
- Application of threshold(s)
- Prioritisation
- Calculation of BZ-shares
- Treatment of flows related to other CCRs[5]

These sub-steps are detailed in the following subsections. Because this report will only consider isolated CCRs, the treatment of flows related to other CCRs is not.

Netting

The flow shares for each flow type are either relieving or burdening with respect to the direction of the total flow on the element. The relieving and burdening flows shall be netted in order to obtain only burdening flow shares for each flow type on a single element. The result of the netting is the set of netted flow shares for each flow type per bidding zone in [MW] for each congested element.

It has to be noted that no netting is considered in the current version of the methodology. No netting will thus be applied in this study either.

Application of thresholds

Threshold may be applied on certain flow types in order to allow (and not penalize) part of these flows. Indeed, for example, since the European grid is meshed, loop flows cannot be fully avoided and a small share of loop flows could thus be tolerated.

In this study, a 20 % threshold for loop flows and internal flows, split equally between the contributors is considered. In a case a BZ does not use the complete amount of its threshold, the remaining is separated equally between the other contributors. Note that the final threshold adopted for loop flows only in the ACER decision [3] is 10%[6].

Prioritisation

This step sorts the netted flow shares according to their priority. The prioritisation considered by ACER, and in this study, is:

- Loop flow above threshold
- Internal flows
- Other flows

The "Other flows" category gathers the "PST flows" and the "Exchange flows" or "Allocated flows" (i.e. transit, import and export flows). Note that it is considered that each TSO is individually responsible to provide the required amount of transmission capacity on its critical network elements. Therefore, if exchange flows (regardless of their specific nature) entail an overload on a transmission element[7], the TSO having that transmission element in its zone will be responsible for the congestion management, and the congestion management costs will be allocated to that TSO. For that reason, no distinction is done between transit/import/export flows. The same rationale applies to PST flows.

[5] A specific CCR is connected to other CCRs. Therefore, the power exchanges with bidding zones outside the CCR under study will entail flows on transmission elements within that CCR.

[6] The two methodologies are equivalent for a system with two BZ, but slightly different for a system with more than two. For example, in a system with four BZs, with the 20%-rule, 5% will be allocated to internal flows and 15% to loop flows.

[7] It must be emphasized that this situation is unlikely to happen, since the capacity available for exchange flows is explicitly restricted at the level of the market.

Calculation of Bidding Zone shares

The netted flow shares above the thermal limit resulting from the prioritization are considered responsible for the congestion proportionally to their value above the limit. Moreover, each flow type is associated to a given bidding zone:

- Loop flows: the zone responsible of the loop flows
- Internal flows: the zone in which the transmission element is located
- Other flows: the zone in which the transmission element is located

For cross-border elements, the responsibility for the "Other flows" category is split 50/50 between the two bidding zones to which the line is connected.

The fraction of responsibility of the congestion can thus be determined between the bidding zones.

2.3.2 Toy model application

The threshold and the prioritisation detailed here above are applied on the flow decomposition presented in Table 3, as presented in Figure 8.

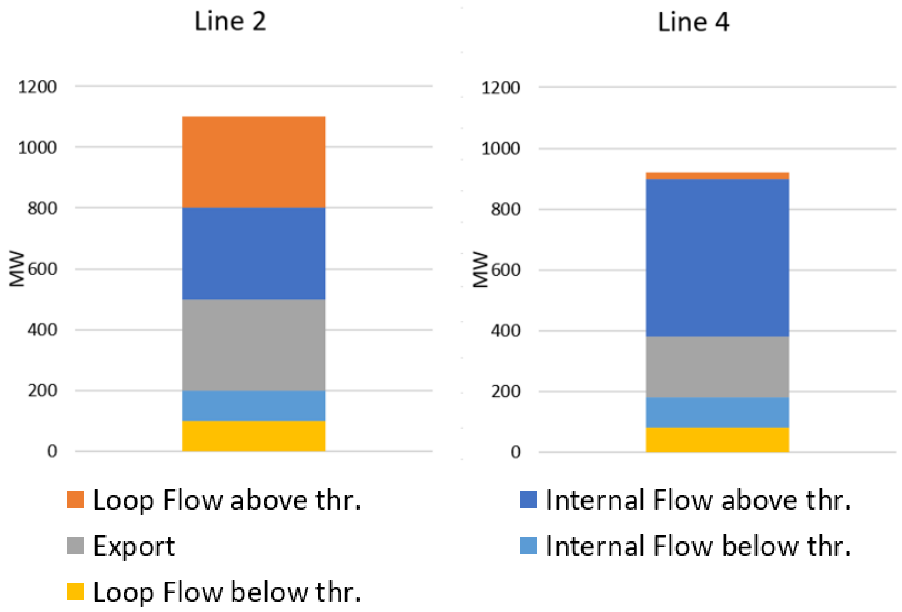


Figure 8: Prioritisation of the flows on the congested element, toy model.

Table 4 presents the flow shares exceeding the thermal limit (e.g. 1000MW for L1 and 800MW for L2), based on which the "Bidding Zone shares" can be computed. Note that these results are sensitive to the tolerated amount of loop flows (i.e. to the chosen threshold).

	L2	L4
Loop flows	100 MW	20 MW
Internal flows	0 MW	80 MW
Export/Import	0 MW	0 MW
BZ A	100%	80%
BZ B	0	20%

Table 4: Flow share above thermal limit and BZ share, toy model.

2.4 Mapping

2.4.1 Methodology

The mapping aims at assigning the cost of the remedial actions to the congested network elements. Four mapping methodologies were first detailed in [2] and an additional methodology has been proposed by ACER in [3]. These five methodologies are :

- Volume Based Mapping (VBM)
- Improved Volume Base Mapping (iVBM)
- Shadow price Mapping (SBM)
- Individual optimisation based Mapping (IOBM)
- Restricted individual optimisation based mapping (RIOBM)

As mentioned previously, the adopted methodology in the ACER decision [3] is the LCBM, called RIOBM in this report.

The first step of each method consist in distributing the total congestion management cost to each hour of the period under study, according to the relative redispatching volume-share per hour.

Volume Based Mapping (VBM)

The cost allocation of the VBM is based only on the global relieve of the congestion after all the remedial actions. The cost allocated to the congestion elements ($c(i)$, cost allocated to the element i) are computed as:

$$r(i) = \frac{F_{i,before} - F_{i,max}}{F_{i,before} - F_{i,after\ all}} \tag{1}$$

$$c(i) = \frac{r(i)}{\sum_j r(j)} C_{all} \tag{2}$$

where $r(i)$ reflects the global utility of all the remedial actions on the elements i, $F_{i,before}$ is the flow on the elements i before any remedial actions, $F_{i,max}$ is the maximum allowable flow on the element i, $F_{i,after\ all}$ is the flow on element i after all remedial actions and C_{all} corresponds to the total cost of the remedial actions.

Improved Volume Based Mapping (iVBM)

The iVBM cost allocation methodology is based on the global relieve of the congestion after all remedial actions (as the VBM) and on the individual relieve of each congestion after each remedial action. The cost of each remedial action is allocated to the congested elements proportionally to the product of the global and individual relieve as detailed in Appendix 7.1.1.

Shadow price Mapping (SBM)

This method allocates the redispatch cost based on the shadow price of the line constraints. The algorithm consists of a loop that increases the thermal limit of the binding constraints by a specific but small quantity[8] per step until there is no more remedial actions applied and allocates the delta in the cost per optimisation rounds to the current binding lines proportionally to their shadow price, as detailed in the document [2] "Common methodology for redispatching cost sharing for the Core CCR in accordance with Article 74 of Commission Regulation (EU) 2015/1222 of 24 July 2015".

Individual Optimisation based Mapping (IOBM)

This methodology allocates the redispatch cost to the congested elements proportionally to the cost of solving each congestion alone. For each congested network element, a remedial action optimization algorithm is run in order to solve the given congestion. During this individual

[8] I.e. by x MW where x is small compared to the thermal rating of transmission elements

optimization, a side condition for the other lines is defined such that for other overloaded lines: $F_{after} \leq F_{before}$, and for other non-congested lines: $F_{after} \leq F_{max}$.

Restricted Individual Optimisation Based Mapping (RIOBM)

This methodology computes the less costly option to solve individually each congestion based on a linear combination of the actual remedial actions used for the redispatch and allocates the remedial action cost to the congested elements proportionally to this cost. This methodology is thus similar to the IOBM but it restricts the remedial actions that could be used to solve each individual congestion to only the ones used to solve all the congestions simultaneously (i.e. to the ones used for the general redispatch process).

2.4.2 Toy model application

Table 5 shows the results obtained by the application of the aforementioned methodologies on the toy model. Three methodologies lead exactly to the same results: for the VBM, the IVBM and the RIOBM, 40% of the congestion management cost is allocated to the line L2 (between buses B1 and B2) and 60% of the congestion management cost is allocated to the line L4 (between buses A1 and A2). The other two methodologies increase the share of L4 in the congestion management cost: 75% and 82.8% of the congestion management cost is allocated to the line L4, for the IOBM and the SBM, respectively.

	L2 [€/h]	L4 [€/h]
VBM	3000	4500
IVBM	3000	4500
SBM	1287	6213
IOBM	1875	5625
RIOBM	3000	4500

Table 5: Mapping results, toy model.

2.5 Multiplication

In order to obtain the costs for each network element per bidding zone and hour, the costs mapped to each network element (outcome of the mapping) is multiplied with the respective bidding zone share per network element (outcome of the transformation).

Based on the results from the “Transformation” and “Mapping”, the total redispatch cost can be allocated between the two bidding zones. Table 6 shows the results for the five different mapping methodologies. Because the mapping of the costs to transmission elements is the same for VBM, IVBM and RIOBM, the allocation of congestion management costs per zone is the same. For these three methodologies, the major part (88%) of the congestion management costs is allocated to zone A. The trend is similar for the other two methodologies: the part of the congestion management costs allocated to zone A is also higher than 80%. This fact is a natural consequence of the results of the transformation step.

	BZ A [€/h]	BZ B [€/h]
VBM	6600	900
IVBM	6600	900
SBM	6247	1243
IOBM	6375	1125
RIOBM	6600	900

Table 6: Cost allocation for each methodology, toy model.

3 Preliminary assessment of mapping methodologies

In order to compare the different mapping methodologies, various criteria could be defined. The CACM mentions nine requirements in article 74 (§6) for any redispatching and countertrading cost sharing methodology, among which "*the methodology [...] shall [...] ensure a fair distribution of costs and benefits between the TSOs involved*" and "*the methodology [...] shall [...] provide incentives to manage congestion, including remedial actions and incentives to invest effectively*". The CACM requires thus **fairness** and **incentive compatibility**, which will constitute two important criteria to assess mapping methodologies. These two criteria are defined in the following sections and assessed based on the results of the toy model.

Although not explicitly mentioned in the CACM, it appears important for any methodology to be easily implementable, i.e. to be clear, to not rely (too much) on implementation choices, and to provide results with a limited computational burden. In particular, the clarity and the independence of the results towards implementation choices are prerequisite for a methodology complying "with the principles of transparency", which is a requirement of the CACM. Since an application on a larger test system is necessary in order to correctly assess the **practicality** of a methodology, this criterion is only presented in the second chapter.

3.1 Fairness

One of the objectives of the development of a formal methodology for cost sharing of redispatching and countertrading was to allocate the congestion cost to the responsible of this congestion, which can be referred as the "polluter-payer" principle. In this context, loop flows are considered as the "polluters" of the system. The bidding zone responsible of the loop flows leading to a congestion should thus be the one carrying the redispatch cost. Furthermore, as a corollary of the "polluter-payer" principle, in case several congestions must be managed simultaneously, BZs responsible of loop flows on congested elements associated to high congestion management costs should pay more than BZs responsible on loop flows on congested elements associated to low congestion management costs. However, a straightforward application of such a "polluter-payer" criterion in order to assess the fairness of a cost-sharing methodology does not appear feasible for two main reasons: a certain level of loop flows are inevitable in a meshed grid, and congestions are interlinked, and so congestion management costs. For instance, the total congestion management cost is usually different from the sum of the costs related to the management of every single congestion as if it was the only one.. Consequently, alternative criteria considering implicitly the "polluter-payer" principle must be found.

Several criteria could be used in order compare the mapping methodologies from a fairness point of view. In this study, it is proposed to use the outcome of a nodal optimization is taken as a reference, since it fully aligns market and grid operation and renders congestion management obsolete as a result (redispatch costs are zero). The metric used for this comparison is the socio-economic welfare (SEW), which is defined as follows for a bidding zone i:

$$\text{Socio-economic welfare}_i = \text{Consumer surplus}_i + \text{Producer surplus}_i + \text{Congestion rent}_i + \text{Redispatch cost}_i$$

where the consumer surplus corresponds to the difference between consumers' willingness to pay and the market price paid for electricity, the producer surplus equals profits (variable revenues minus variable generation costs) and the congestion rent is the regional price difference captured by TSOs in case lines are congested. The redispatch cost supported by bidding zone i depends on the allocation methodology, which is the subject of the analysis. Note that the socio-economic welfare of the whole region (bidding zones considered together) is independent from the mapping methodology applied[9]. Hence, the fairness criterion looks at the distribution of the global socio-economic welfare among bidding zones and a methodology that highlights a "smaller distance" to the optimum is ranked higher. Note that in this comparison, we only look at socio-economic welfare and not at the change of surplus between consumers, producers and network operators. They are equally weighted. The formulas to compute the socio-economic welfare for the two approaches are detailed in Appendix 7.2[10].

Table 7 presents the difference between the zonal SEW computed with the five considered mapping methodologies with the SEW obtained from the nodal approach. The difference is thus positive when the SEW of the zone is smaller in the nodal approach, and negative when the SEW of the zone is larger in the nodal approach. For all methodologies, it can thus be observed that the use of a zonal market entails a lower SEW for zone B compared to a nodal approach, for any mapping methodology used. It means that a too important share of the congestion management costs appears to be allocated to zone B. Nevertheless, as shown in section 2.5, only a very small share of the congestion management costs is allocated to zone B (between 12 and 18 percent, depending on the methodology). Even if zone A would have to bear 100 percent of the redispatch cost, this imbalance would subsist, at a level of 4125 €/h. Consequently, it can be concluded that all methodologies go in the good direction on this aspect, but VBM, IVBM and RIOBM are closer to the ideal sharing key defined by comparison with the nodal approach. Note that, although the iVBM, SBM, IOBM and RIOBM methods are able to link specific congestions to specific remedial actions, which is theoretically a requirement of the "polluter-payer" principle, in practice, on this example, the VBM method, unable to perform this link, does not appear as less fair.

	BZ A [€/h]	BZ B [€/h]
VBM	5025	-5025
IVBM	5025	-5025
SBM	5309	-5309
IOBM	5250	-5250
RIOBM	5025	-5025

Table 7: Difference of the zonal welfare for the different methodologies with nodal welfare.

3.2 Incentive compatibility

According to the CACM, a congestion cost allocation methodology should "*provide incentives to manage congestion, including remedial actions and incentives to invest effectively*". It implies that a TSO investing to increase the transmission capacity and/or to reduce the amount of loop flows it generates should see a decrease of its congestion management cost, such that it has a financial incentive for that investment. Similarly, it should not incentivize a TSO to take an action that could reduce the overall SEW.

In order to understand if the different congestion cost allocation methodologies are incentive-compatible, three variants of the toy model are first studied. In a second step, the impact of the PST setting on the congestion cost allocation as well as the impact of the change of BZ definition are studied.

Grid topology variants

1. *What if the TSO of zone B increases the thermal capacity of the congested line?*

[9] This only holds if we assume demand to be fixed (i.e. not price dependent). The optimization of SEW boils down to a cost minimization.

[10] Note that, in the nodal approach, there are several possibilities to decompose the overall congestion rent into contribution of individual transmission elements. A specific choice is used in this study, and it must thus be emphasized that the results could be sensitive to the chosen possibility.

Although the line L2 in Figure 9 is not anymore a binding constraint after redispatch, it appears overloaded as a result of the market coupling and all the mapping methodologies allocate a cost to that line. It could thus appear natural for the TSO of zone B to increase the thermal capacity of that line[11], even if that action alone will not be sufficient to reduce the total redispatch cost[12]. This first example studies thus the impact of an increase of the thermal capacity of L2 from 1000MW to 1100MW. To be incentive-compatible, such a grid reinforcement should not lead to an increase of the redispatch cost borne by zone B.

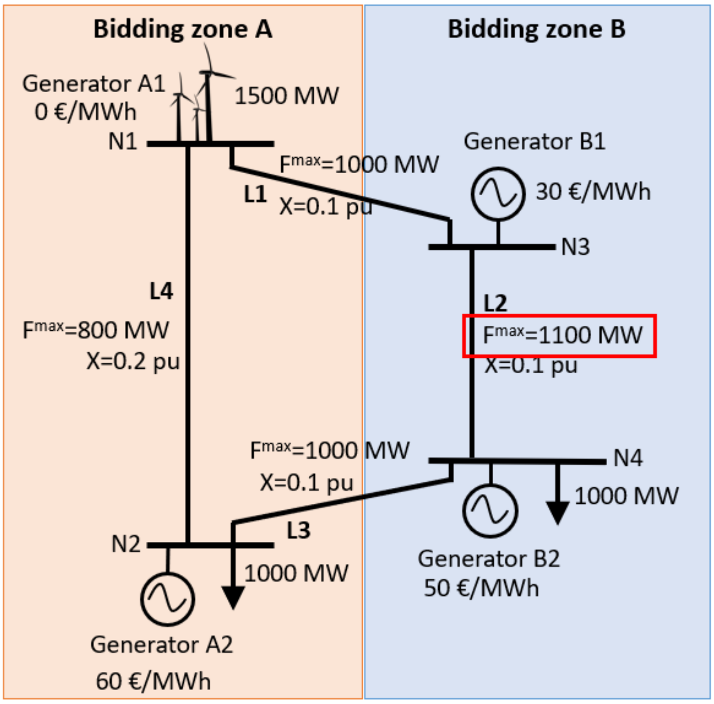


Figure 9: Variant 1 of the toy model.

The solution of the FBMC is identical to the one presented in Figure 3. There is no more congestion in zone B. The only congestion is on line L4, and is still fully explained by loop flows. The redispatch is identical to the redispatch of the initial model but for this situation, and for all mapping methodologies, zone B will support alone the overall redispatch cost.

The increase of the thermal capacity of the congestion lines in order to avoid a congestion within zone B leads to an increase of the cost for zone B. This highlights a shortcoming observed for all mapping methodologies.

2. *What if B artificially decreases the thermal capacity of the congested line?*

For this example, it is considered that the TSO of zone B artificially derates the line L2 by decreasing the thermal capacity from 1000MW to 945MW.

[11] For example by reconductoring it.
[12] The total redispatch cost could be reduced for instance if the thermal capacity of line L4 is also increased.

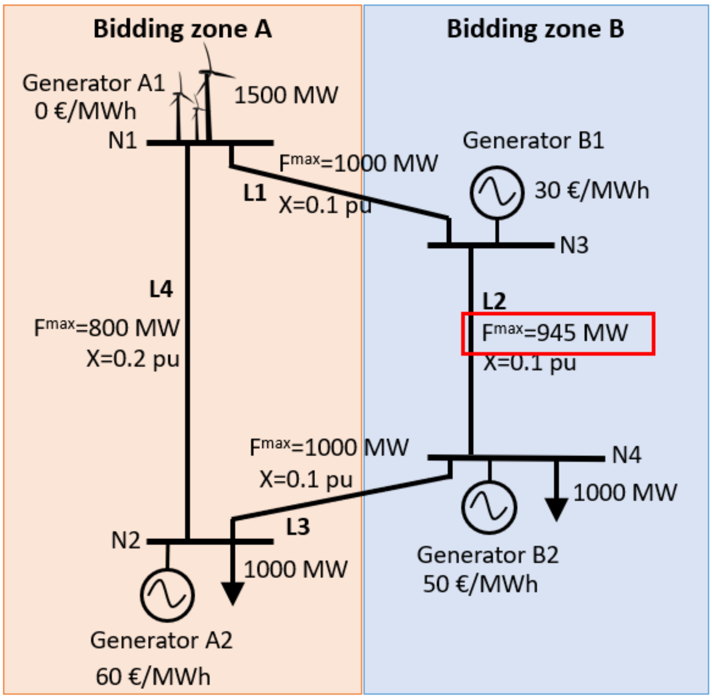


Figure 10: Variant 2 of the toy model.

The solution obtained after the redispatch is different to the solution of the initial model, see Figure 11.

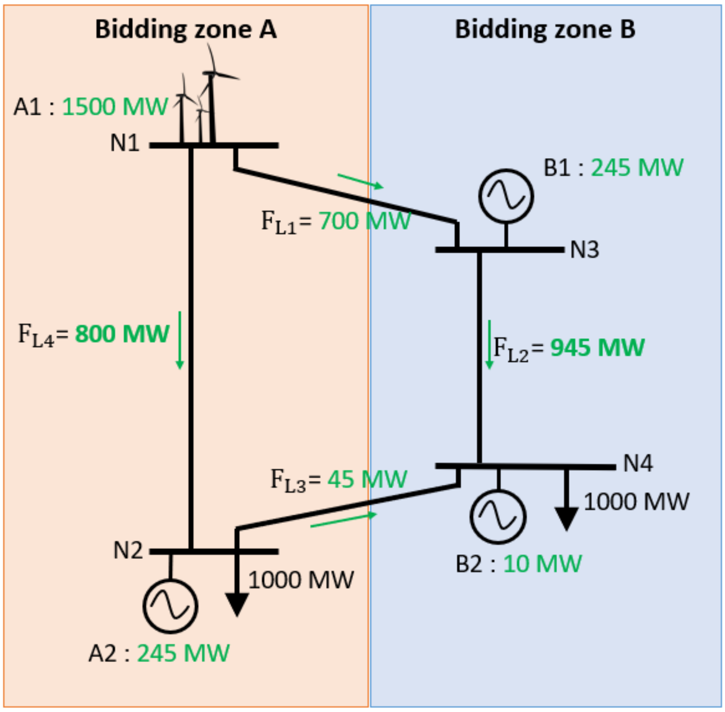


Figure 11: Variant 2 of toy model, solution after redispatch.

The redispatch cost is increased to 7550€.

The cost allocated to the two zones for the different mapping methodologies are :

	ZA [€/h]	ZB[€/h]
VBM	6795	755
IVBM	6792	758
SBM	6479	1071
IOBM	6554	996
RIOBM	6795	755

Table 8: Cost allocation, variant 2 of toy model.

It is noticed that, although the redispatch cost is higher and the socio-economic welfare is thus lower, the absolute redispatch cost allocated to Zone B is lower than in the base case. The TSO of zone B would thus have an incentive to artificially derate its transmission line, whatever the mapping methodology is. This example illustrates that a high transparency on TSOs' discretionary actions is required to avoid the use of these actions for the sole benefit of a TSO.

Impact of PST

The aim of this variant is to analyse the impact of PST settings in the initial Common Grid Model (CGM) used to compute the transmission capacity available to the market[13]. Indeed, these settings are not necessarily neutral, they will define the base case and can impact congestions.

To study the impact of the initial setting of the PST, the model as described in Figure 12 is used.

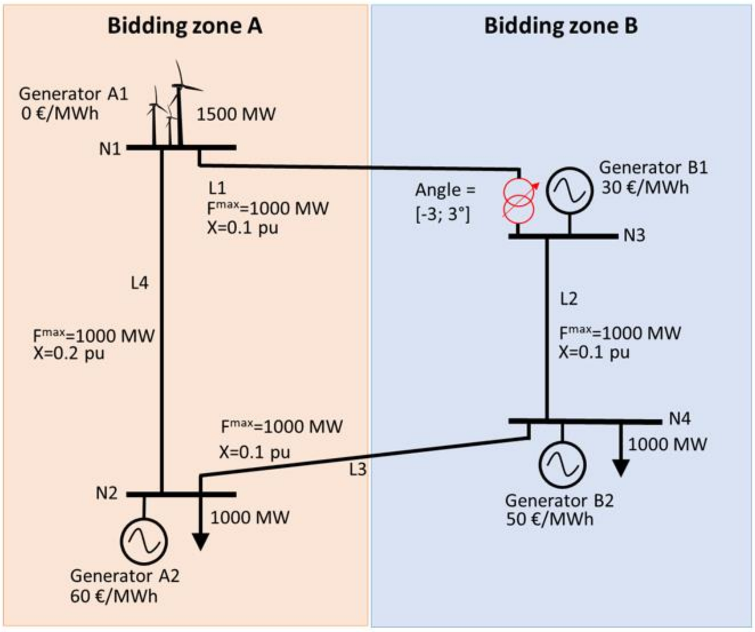


Figure 12: Impact of the PSTs, toy model.

The dispatch obtained is identical for all initial angles in the range studied ([-3°, 3°]) and is detailed in Table 9.

[13] For example the two-day forecast (D2CF) files for the day-ahead market.

Generator	FBMC
A1	1500 MW
A2	0 MW
B1	500 MW
B2	0 MW

Table 9: Dispatch, study of impact of PSTs, toy model.

Line flows for the different initial PST settings are presented in Table 10.

Lines	-3° [MW]	-2° [MW]	-1° [MW]	0° [MW]	1° [MW]	2° [MW]	3° [MW]
L1	704.7	669.8	634.9	600.0	565.1	530.2	495.3
L2	1204.7	1169.8	1134.9	1100.0	1065.1	1030.2	995.3
L3	204.7	169.8	134.9	100.0	65.1	30.2	-4.7
L4	-795.3	-830.2	-865.1	-900.0	-934.9	-969.8	-1004.7

Table 10: Flows on lines for different initial PST settings, toy model.

For the redispatch, the position of the PST is optimized. The optimal PST angle is -1.72°, and the dispatch obtained is presented in Table 11.

Generator	Redispatch
A1	1500 MW
A2	0 MW
B1	300 MW
B2	200 MW

Table 11: Redispatch with PST, toy model.

In this case, the redispatch cost is equal to 4000 €/h.

The flow share for each congested lines is presented in Table 12.

	-3°		-2°		-1°		0°		1°		2°		3°	
	L2	L4	L2	L4	L2	L4	L2	L4	L2	L4	L2	L4	L2	L4
Loop flow	100%	0%	100%	20%	100%	20%	100%	20%	100%	15%	100%	12%	0%	10%
Internal flow	0%	0%	0%	80%	0%	80%	0%	80%	0%	85%	0%	88%	0%	90%
Import/Export	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
PST flow	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 12: Flow share for different initial PST settings, toy model.

The congestion cost allocation obtained is presented in the Table 13 for the VBM, IOBM, iVBM and SBM methodology.

	-3° [€/h]		-2°[€/h]		-1°[€/h]		0°[€/h]		1°[€/h]		2°[€/h]		3°[€/h]	
	ZA	ZB	ZA	ZB	ZA	ZB	ZA	ZB	ZA	ZB	ZA	ZB	ZA	ZB
VBM	4000	0	3600	400	3600	400	3600	400	3700	300	3760	240	3600	400
IOBM	4000	0	3879	121	3740	260	3600	400	3595	405	3592	408	3600	400
iVBM	4000	0	3600	400	3600	400	3600	400	3700	300	3760	240	3600	400
SBM	4000	0	3600	400	3600	400	3600	400	3700	300	3760	240	3600	400

Table 13: Congestion cost allocation for the different mapping methodologies, toy model.

The results indicate a strong dependence of the final cost allocated to each zone on the initial PST setting. Indeed, for example, Zone B can manage to avoid paying congestion cost if it sets the PST lower than -3°.

It must be emphasized that the analysis above assumes that the mapping is performed on the basis of power flows resulting from the outcome of the market clearing using the PST setting of the initial CGM. There are two possibilities to eliminate the dependance of the cost sharing on that initial setting. The first is to perform the mapping on the basis of power flows resulting from the outcome of the market clearing using the optimized PST setting. The second would be to do the mapping with the PST set initially to 0. It has to be noted that the PST actions are taken into account in the methodology for the RIOBM.

Finally, these conclusions can be transposed to the grid topology, because topological actions are other important non-costly remedial actions.

Change of Bidding Zone definition

The aim of this variant is to study the impact of the change of BZ definition on the allocation of the redispatch cost and on the repartition of the SEW. In the example considered, Zone A is split in Zone A1 and Zone A2.

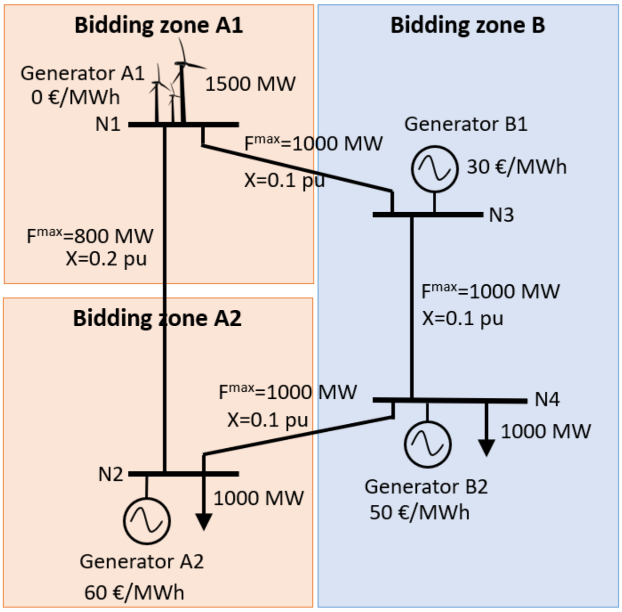


Figure 13: Impact of BZ definition, toy model.

In this case, the dispatch obtained after the FBMC is presented in Table 14.

Generator	FBMC
A1	1250 MW

A2	0 MW
B1	750 MW
B2	0 MW

Table 14: Dispatch, study of BZ definition, toy model.

The corresponding flows on the lines are presented in Figure 14.

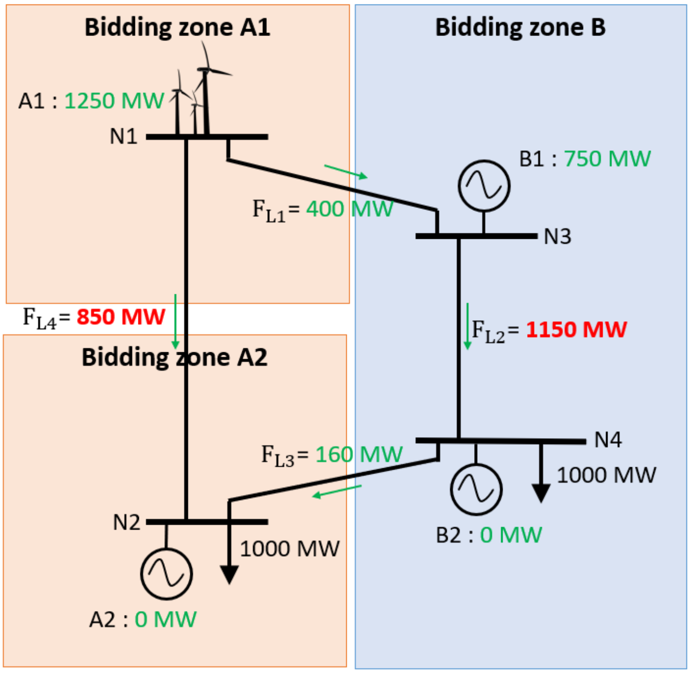


Figure 14: Impact of BZ definition, solution after dispatch, toy model.

L4 and L2 are thus still congested. However, the solution after redispatch is identical than the one of the base case and the redispatch cost is null.

The repartition of the SEW is identical for all mapping methodologies and different than from the base case. The difference of zonal SEW compared to the base case is presented in Table 15, the SEW of Zone A being the sum of the SEW of Zone A1 and A2.

	BZ A [€/h]	BZ B [€/h]
VBM	-9150	9150
IVBM	-9150	9150
SBM	9473	9473
IOBM	-9375	9375
RIOBM	-9150	9150

Table 15: Difference of zonal SEW with base case.

It can be noted that the SEW of Zone A is lower with the split of its BZ while the cost of redispatch is decreased for both zones. From the point of view of zone A, the incentive to split is thus ambivalent, as both the redispatch cost and the SEW decrease.

Conclusion

Through the different variants presented in this section it was highlighted that TSOs may face perverse incentives regarding grid investment, or initial PST settings, independently of the mapping methodology considered. It has to be highlighted that these effects should not be seen as a generality, but rather as effects that can appear if precautions are not taken.

4 Detailed assessment of mapping methodologies

This chapter applies the methodology presented in the previous chapter to a more realistic case study, in order to provide an in-depth assessment of these methodologies. Indeed, in the previous chapter, and in the reference documents available, the congestion cost allocation methodology, and more specifically the mapping methodologies, were presented and discussed theoretically. The different methodologies were not fully applied to a concrete example in order to compare the results and highlight their potential drawbacks.

First, the model used is presented. Then the methodology is clarified, and additional remarks regarding the mapping methodologies are made. Finally the results of the application are presented and discussed.

4.1 Model

The case study under consideration is the adaptation of the 3-zone IEEE RTS proposed by [4]. The system contains 73 buses and 125 branches (transmission lines and transformers). The peak load for each of the three areas is 2850 MW. The peak load for the overall system is then 8417 MW. The off-peak load for the overall system is 3643 MW. Along the year, the load is modulated in each zone according to a dedicated load profile. The average load factor is 67.8%. The total conventional capacity (nuclear, coal, gas and oil) is 9120 MW, sufficient to cover the peak load. In addition, 3900 MW of wind energy is installed, mainly in zone 2, with an average capacity factor of 27%. Hourly wind profiles are different for each zone, but with a high correlation.

Table 16 details the installed capacity per zone and the marginal cost range per generation type.

	Zone 1 [MW]	Zone 2 [MW]	Zone 3 [MW]	Total [MW]	Marginal cost [€/MWh]
Coal	0	1700	2200	3900	[35.2, 36.8]
Gas	1200	750	750	2700	[46.6, 47.6]
Nuclear	1500	0	0	1500	[14.1, 14.2]
Oil	420	300	300	1020	[156, 157.4]
Wind	200	3200	500	3900	0

Table 16: Installed capacity per zone and marginal cost range, test model.

The system is presented in Figure 15. The nodes starting with 1 correspond to Zone 1, with 2 to Zone 2 and with 3 to Zone 3.

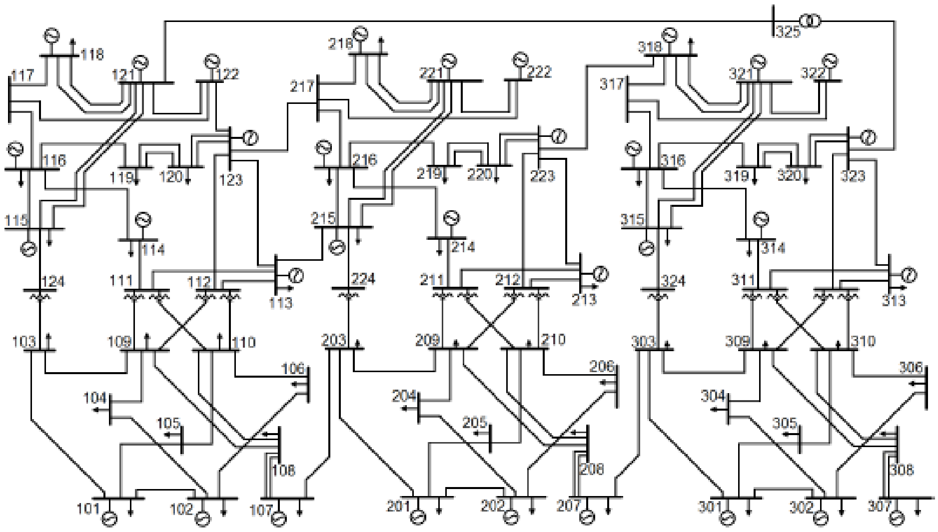


Figure 15: Representation of the test system.

4.2 Methodology

The methodology as described in chapter 2 to simulate the market clearing, the redispatch process and the congestion cost allocation is followed. However, N-1 security constraints are now enforced to be more realistic. Consequently, the power flows on a transmission element must be below the thermal limit not only for the normal (N-0) state, but also following any single contingency. The simulation is performed on an hourly basis and for an entire year.

The implementation of the different methodologies allowed to assess their practicality and highlighted some gaps in the process. The practicality of the different methods is described in Section 4.4. As methodologies have not been publicly described in a way that allows a straightforward implementation without any additional working assumption, some hypotheses had to be taken to fully implement them. These hypotheses are detailed in the following sections.

4.2.1 Improved Volume Base Mapping (iVBM)

In order to apply the methodology described in the previous chapter, the remedial actions have to be studied independently. To keep a balance between the load and the generation, the variation of a generator output must be compensated. However, the increase of a generator cannot directly be linked to the decrease of another. In order to analyse the impact of the variation of the generation output independently, one or multiple slack nodes have thus be defined to balance the load and the generation. It has to be noted that the solution obtained is thus dependent on the slack node defined.

In the model developed for this study, the distributed slack nodes were considered :

- For the increase of a generator output, it is considered that all the generators participating to downward redispatch compensate the production increase proportionally to their global decrease.
- For the decrease of a generator output, it is considered that all the generators participating to upward redispatch compensate the production increase proportionally to their global increase.

4.2.2 Shadow price Mapping (SBM)

As detailed in the previous chapter, the algorithm consists of a loop that increases the thermal limits of the binding constraints by a specific but small quantity per step until there is no more remedial actions applied. However, the condition "until there is no more remedial actions applied" has to be defined. Indeed, because the FB market constraints are not considered in the successive iterations of the SBM algorithm (a full power flow model is implemented), the dispatch given by these iterations might never reach exactly the one of the market and might become more economical that the one of the market when the thermal limits of the binding constraints are sufficiently increased. The aforementioned condition can be interpreted in several ways:

a) Until the production cost equals the production cost of the FB market;
b) Until there are no more binding constraints from the capacity of transmission elements

It has to be noted that for the first option, some of the initially overloaded elements might not appear as binding constraints. Furthermore, for either options considered, the binding lines of a round of the loop might not be part of the initially overloaded elements. If part of the remedial action cost is allocated to a line which is not part of the initially overloaded elements, it will not be possible to assign this cost to a zone, and money will be missing at the end of the process. An option to alleviate this issue would be to assign the cost change per optimization round only to the lines that are part of the initially overloaded elements. If for a round no lines are part of the initially overloaded elements, the cost change is reported for the next round.

4.2.3 Individual Optimisation Based Mapping (IOBM)

In addition to the methodology presented in the explanatory document, a post-processing of the values obtained is performed to avoid negative mapping values. Indeed, because each individual redispatch problem deals with a unique specific network element, without enforcing constraints for other network elements, the solution of an individual redispatch problem can lead to a negative redispatch cost (i.e. total generation cost lower than the result of the flow-based market). Note however that, when the parameters of the flow-based market coupling are optimally estimated[14], the total redispatch cost is always positive.

The following post processing methodology, based on the post processing of the RIOBM methodology is used:

a) If less than half of individual redispatch costs are lower than 0, these weights shall be set to 0;

b) If half or more of individual redispatch costs are lower than 0, the opposite of the lowest negative individual redispatch cost shall be added to all individual redispatch costs;

c) If all the individual redispatch costs are the same and equal to 0 or negative, the total redispatch cost is evenly distributed between congested network elements.

It has to be noted that, when individually optimised, many congestions can entirely be resolved with non-costly actions. Then, the individual pictures superposed do not reflect the global picture of common RA optimisation which is a drawback for the IOBM and RIOBM[15].

4.3 Quantitative evaluation

The following sections present the global annual results of the congestion cost allocation to the test system.

First, congestions and total redispatch costs are analyzed. Then, the allocation of the redispatch cost according to the different methodologies is presented. Finally, the results are discussed based on the criteria of "Fairness" and "Practicality". Also, specifics hours are studied independently in order to highlight the variation of results between the methodologies and between different hours.

[14] Which is the case in the simulation process used in this study.

[15] It is expected that this issue will be more severe for IOBM which starts from all available XRAs, while RIOBM is limited to the XRAs triggered by the real RAO.

4.3.1 Congestions and redispatch cost

The average number of congested network elements in the base case or under contingency (i.e. taking into account N-1 situations) per hour per zone is presented in Table 17.

	Number of congested elements
Zone 1	1.8
Zone 2	2.3
Zone 3	69.1
Total	73.2

Table 17: Average number of congested elements per zone.

Most of the congestions occurs in Zone 3. Indeed, the line between the nodes 314 and 316 of Figure 15 is congested in most situations.

The total annual redispatch cost is equal to 19 216k€, which represents an average redispatch cost of 0.38€/MWh.

4.3.2 Congestion cost allocation

Table 18 presents the total annual redispatch cost per zone for the different methodologies as well as the redispatch cost per MWh of load.

	Total redispatch cost [k€/h]			Total redispatch cost [€/MWh$_{load}$]		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
VBM	0.19	0.05	1.95	0.12	0.02	0.93
iVBM	0.15	0.05	2.00	0.09	0.02	0.95
SBM	0.37	0.12	1.70	0.23	0.06	0.81
IOBM	0.15	0.03	2.01	0.09	0.02	0.95
RIOBM	0.17	0.04	1.99	0.10	0.02	0.94

Table 18: Total redispatch cost for the different mapping methodologies.

The majority of the redispatch cost is allocated to Zone 3 for all methodologies (78% to 92%), due to the important congestions of line 314-316. Furthermore, total zonal redispatch costs are very close for all methodologies, except for SBM.

4.3.3 Fairness

As detailed in the previous chapter, the criteria of fairness is assessed based on the zonal SEW, with the SEW of the nodal approach as reference.

Table 19 presents the average distance between the zonal SEW of the different methodologies and the nodal reference as well as the average distance from the reference for the different mapping methodologies.

[k€/h]	Zone 1	Zone 2	Zone 3	Average distance	Standard deviation of av. dist.
VBM	0.64	-1.32	0.68	3.21	2.47
iVBM	0.68	-1.32	0.64	3.28	2.46

SBM	0.46	-1.39	0.94	3.23	2.46
IOBM	0.68	-1.30	0.62	3.21	2.46
RIOBM	0.66	-1.31	0.65	3.21	2.45

Table 19: Distance with nodal SEW reference.

From these results, it can be noted that the VBM, IOBM and RIOBM methodologies have the smallest average distance with the nodal reference and can thus be considered as the "fairest" methodologies. Nevertheless, for all methodologies, it can be observed that the use of a zonal market entails a lower total SEW for zone 2 compared to a nodal approach, for any mapping methodology used. Although the natural interpretation would be that a too important share of the congestion management costs is allocated to zone 2, Table 18 shows that it is not the case. Even if zone 2 had not to assume any redispatch cost, this imbalance would subsist, at a level of 1.27 k€/h. This impossibility to reach the same distribution of the SEW than the one obtained with a nodal approach was already pointed out in section 3.1.

Table 19 shows also that the standard deviation of the average distance is similar for the five methodologies under study. Finally, the zonal trend of the average difference with the reference is similar for the different mapping methodologies.

4.3.4 Hourly results

In this section the congestion cost allocation of specific hours is studied in order to highlight the origin of the variation of the cost allocation. Two specific hours are studied with contrasted splits of the congestion management cost between the three zones: in case A, almost all the congestion management cost is allocated to zone 3 (in line with the average trend observed in Table 18), and, in case B, a significant part of the congestion management cost is allocated to zone 1.

4.3.4.1 CASE A

This moment corresponds to Tuesday the 2nd of January at 10am.

The load per zone and the solution after the flow-based market coupling is presented Table 20.

[MW]	Zone 1	Zone 2	Zone 3
Load	2094	2423	2619
Coal	0	1310	1918
Gas	43	0	0
Nuclear	1500	0	0
Oil	0	0	0
Wind	108	2049	210
Total gen.	1651	3359	2127

Table 20: Load and generation per zone for FBMC, case A.

The total production cost is 138.5 k€.

The solution after redispatch is presented in Table 21.

[MW]	Zone 1	Zone 2	Zone 3
Coal	0	1168	1554
Gas	43	142	364
Nuclear	1500	0	0

Oil	0	0	0
Wind	108	2049	210
Total gen.	1651	3359	2127

Table 21: Generation per zone after redispatch, case A.

The total production cost is 144.6 k€ after redispatch. The redispatch cost is thus equal to 6.1k€.

The congestion cost allocation for the different methodologies are presented in Table 22.

[k€/h]	Zone 1	Zone 2	Zone 3
VBM	0.0	0.4	5.6
iVBM	0.0	0.3	5.8
SBM	0.0	1.4	4.6
IOBM	0.0	0.1	5.9
RIOBM	0.0	0.1	5.9

Table 22: Congestion cost allocation, case A.

For this given hour, the majority of the total congestion cost is allocated to zone 3.

Indeed, as for an important part of the hours under study, the line 314-316 is highly congested. Indeed, this line is already congested in the base case (without contingency), and close to 100% of the flow above the thermal limits are allocated to zone 3.

The percentage of the redispatch cost associated to this line, per mapping methodologies is detailed in Table 23.

	Cost for L314-316
VBM	74%
iVBM	74%
SBM	47%
IOBM	93%
RIOBM	95%

Table 23: Cost mapped for line 314-316, case A.

It is noticed that the difference of element cost allocation between methodologies is important for this example. The SBM methodologies allocates only 47% to the line 314-316, the rest being spread among 18 other lines (and in particular line 208-209 and 208-210).

Table 24 presents the distance between the zonal SEW for the different methodologies and the nodal reference. For this particular hour, it is now zone 1 that has a SEW welfare lower than the one given by a nodal market, although Table 22 shows that zone 1 pays (almost) no congestion management cost. It echoes comments formulated in section 3.1 and in section 4.3.3. Zone 2 and zone 3 have thus together a SEW higher than the one given by a nodal market. The SBM approach does not appear fair, as an additional transfer of SEW appears from zone 2 to zone 3. The other five methodologies lead to different sharing keys of the SEW surplus between zone 2 and zone 3, but without entailing an additional transfer between these zones.

[k€/h]	Zone 1	Zone 2	Zone 3	Average distance
VBM	-0.91	0.57	0.33	1.12
iVBM	-0.88	0.70	0.17	1.14
SBM	-0.89	-0.47	1.35	1.68
IOBM	-0.88	0.86	0.02	1.23
RIOBM	-0.88	0.88	0.00	1.24

Table 24: Distance with nodal SEW reference, case A.

4.3.4.2 CASE B

This hour corresponds to Thursday the 19th of December at 10am.

Table 25 presents the load per zone and the solution after the flow-based market coupling. The total production cost is 275.7 k€.

[MW]	Zone 1	Zone 2	Zone 3
Load	2850	2627	2732
Coal	0	1700	2200
Gas	1200	750	477
Nuclear	1500	0	0
Oil	0	0	0
Wind	25	353	3
Total	2725	2803	2680

Table 25: Load and generation per zone for FBMC, case B.

The solution after redispatch is presented in Table 26.

[MW]	Zone 1	Zone 2	Zone 3
Coal	0	1700	2151
Gas	1090	750	500
Nuclear	1500	0	0
Oil	93	0	43
Wind	25	353	3
Total	2708	2803	2697

Table 26: Generation per zone after redispatch, case B.

The total production cost is 291.1 k€ after redispatch. The redispatch cost is thus equal to 15.4 k€.

Table 27 presents the congestion cost allocations for the different methodologies.

[k€]	Zone 1	Zone 2	Zone 3
VBM	8.0	0.0	7.3
iVBM	6.0	0.0	9.4
SBM	9.6	0.0	5.7
IOBM	11.3	0.0	4.1
RIOBM	8.9	0.0	6.5

Table 27: Congestion cost allocation, case B.

For this given hour, an important part of the total congestion cost is allocated to zone 1. This hour corresponds to the annual peak load of zone 1, leading to the congestion of lines 103-109, 105-110 and 106-110 under some contingencies.

	L103-109	L105-110	L106-110	L306-310	L314-316
VBM	12%	6%	34%	16%	31%
iVBM	8%	5%	26%	19%	42%
SBM	11%	11%	40%	26%	11%
IOBM	16%	8%	50%	9%	18%
RIOBM	12%	6%	40%	7%	35%

Table 28: Cost mapped for the congested lines, case B.

Table 29 presents the distance between the zonal SEW for the different methodologies and the nodal reference. For this particular hour, it is now zone 2 that has a SEW welfare lower than the one given by a nodal market, although Table 27 shows that zone 2 pays no congestion management cost. This situation has already been commented. Zone 1 and zone 3 have thus together a SEW higher than the one given by a nodal market. The IOBM approach does not appear fair, as an additional transfer of SEW appears from zone 1 to zone 3. The other five methodologies lead to different sharing keys of the SEW surplus between zone 1 and zone 3, but without entailing an additional transfer between these zones.

[k€]	Zone 1	Zone 2	Zone 3	Average distance
VBM	2.01	-2.68	0.67	3.41
iVBM	4.09	-2.68	-1.42	5.09
SBM	0.41	-2.68	2.27	3.53
IOBM	-1.26	-2.68	3.93	4.92
RIOBM	1.19	-2.68	1.49	3.28

Table 29: Distance with nodal SEW reference, case B.

4.4 Qualitative evaluation : practicality

As mentioned in the previous chapter, it is proposed to compare the methodologies based on their practicality of implementation such as clarity and easiness to compute.

The table here under summarizes the assessment of the practicality of the five mapping methodologies under study.

Methodology	Clarity	Easiness to compute
VBM	+ Only global utility	+ No additional LF or optimisation
iVBM	= Global and individual utility - Dependent on the slack node - Possibility of negative values	= Additional LF for each RA
SBM	- Based on shadow price through an iteration loop process (loss of clarity)[16] - Possibility of binding constraints not part of the initially overloaded elements	- Remedial optimisation loop
IOBM	- Possibility of negative values → complex post processing - Need of fallback procedure in particular cases	- Remedial optimisation for each congestion - High computation time - Application of non-costly RAs can be significantly different in individual and global optimization
RIOBM	- Possibility of negative values → complex post processing	- Remedial optimisation for each congestion - Application of non-costly RAs can be significantly different in individual and global optimization

Table 30: Practicality of the mapping methodologies.

[16] As detailed in Section 2.4.1, the SBM methodology requires to compute the shadow prices of the congested elements throughout an iteration loop that increases the thermal limit of the binding constraints by a specific but small quantity per step until there is no more remedial actions applied. This methodology is complex and may lack of clarity.

5 Conclusions

The complete methodology for congestion management costs allocation has been applied to a toy and a test system and the evaluation criteria defined to assess the performance of the different mapping methodologies were :

- **Fairness**
- **Incentive compatibility**
- **Practicality**

Table 31 summarizes the assessment of the mapping methodologies based on these criteria.

Methodology	Fairness	Incentive compatibility	Practicality	
			Clarity	Easiness to compute
VBM	- No linking of specific congestions to specific RAs	Perverse incentive independent of the mapping methodology (based on toy model)	+ Only global utility	+ No additional LF or optimisation
iVBM	No significative difference between the mapping methodologies		= Global and individual utility - Dependent on the slack node - Possibility of negative values	= Additional LF for each RA
SBM			- Based on shadow price through an iteration loop process (loss of clarity) - Possibility of binding constraints not part of the initially overloaded elements	- Remedial optimisation loop
IOBM			- Possibility of negative values → complex post processing - Need of fallback procedure in particular cases	- Remedial optimisation for each congestion - High computation time - Application of non-costly RAs can be significantly different in individual and global optimization
RIOBM			- Possibility of negative values → complex post	- Remedial optimisation for each

			processing	congestion - Application of non-costly RAs can be significantly different in individual and global optimization

Table 31: Assessment of the mapping methodologies.

In conclusion, the assessment has revealed that future work on mapping methodologies should primarily focus on the practicality of the solution. Considerations around fairness and incentive compatibility seem to be less reliant on the methodology applied.

Finally, the analysis allowed to highlight some points in the methodology that need further clarification, especially for the iVBM, SBM and IOBM methodologies.

6 References

[1] European Commission, "*Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (Text with EEA relevance.)*", June 2019.

[2] TSOs of the Core CCR, "Common methodology for coordinated redispatching and countertrading cost sharing for the Core CCR in accordance with Article 74 of Commission Regulation (EU) 2015/1222 of 24 July 2015", February 2019.

[3] ACER, ACER Decision 30-2020 on the Core Capacity Calculation Region TSO's Proposal for the Methodology for Cost Sharing of Redispatching and Countertrading, November 2020.

[4] P. Henneaux, P. Lamprinakos, G. de Maere d'Aertrycke, and K. Karoui, "*Impact assessment of a minimum threshold on cross-zonal capacity in a flow-based market*", in 21st Power Systems Computation Conference.

[5] CREG, "*Document de consultation publique sur la demande d'Elia de dérogation à la marge minimale à mettre à disposition pour les échanges entre zones*", October 2019.

[6] TenneT, "*Request of TenneT TSO B.V. for a derogation from the minimum level of capacity to be made available for cross-zonal trade*", October 2019.

[7] RTE, "*Demande de dérogation de RTE conformément à l'article 16(9) du Règlement 2019/943 – région CORE*", November 2019 .

[8] RTE, "*Demande de dérogation de RTE conformément à l'article 16(9) du Règlement 2019/943 – région Italie Nord*", November 2019 .

7 Appendix

7.1 Formula for mapping methodologies

7.1.1 iVBM

The formula presented in the document [2] "Common methodology for redispatching cost sharing for the Core CCR in accordance with Article 74 of Commission Regulation (EU) 2015/1222 of 24 July 2015" of February 22 2019 was updated by ACER and is presented here under.

$$c_i = \sum_j s_{i,j} \cdot C_j \tag{3}$$

$$s_{i,j} = \frac{rt_{i,j}}{\sum_i rt_{i,j}} \tag{4}$$

$$rt_{i,j} = ri_{i,j} \cdot rg_i \tag{5}$$

$$rg_i = \frac{F'_{b,i} - \max(F_{max,i}, F_{a,i})}{F'_{b,i} - F_{a,i}} \tag{6}$$

$$ri_{i,j} = \frac{F'_{b,i} - \max(F_{max,i}, F_{aRA,i,j})}{F'_{b,i} - \max(F_{max,i}, F_{a,i})} \tag{7}$$

with

c_i	Share of total costs of all XRAs attributed to XNEC i [€]
$s_{i,j}$	Normalized share of the cost of XRA j to be attributed to XNEC i
C_j	Total cost or revenue for applied XRA j [€]
$rt_{i,j}$	Total utility of XRA j on XNEC i
$ri_{i,j}$	Individual utility of XRA j on XNEC i
rg_i	Global utility of all XRAs on XNEC i
$F'_{b,i}$	Adjusted total flow on XNEC i calculated before coordination optimisation [MW]
$F_{max,i}$	Maximum flow on XNEC i [MW]
$F_{a,i}$	Total flow on XNEC i calculated after coordination optimisation [MW]
$F_{aRA,i,j}$	Total flow on XNEC i after application of XRA j [MW]

The following additional rules shall apply for the calculation of variables presented here above :

a) If individual utility $ri_{i,j}$ or global utility rg_i is lower than 0 it shall be set to 0 and if higher than 1 it shall be set to 1;

b) The negative values for share of total costs for XNECs (c_i) shall be set to zero and shared proportionally to all XNECs with final positive c_i;
c) The adjusted total flow $F'_{b,i}$ shall be calculated by (i) using the CGM referred to in Article 4(d), (ii) applying all non-costly remedial actions to it and (iii) calculating the total flow on XNEC *i* using AC load flow calculation
d) In case an XRA has a negative impact on all XNECs and $s_{i,j}$ is zero for each *i*, the cost of such XRA will not be mapped to any XNEC and shall be shared proportionally to all XNECs with final positive c_i.

7.1.2 RIOBM

$$c_i = \frac{r_i}{\sum_i r_i} C^{all} \tag{8}$$

$$r_i = \sum_j \alpha_{i,j} C_j \tag{9}$$

and r_i is calculated by solving the following optimisation:

$$\min_{\alpha,\beta} r_i \tag{10}$$

$$0 \leq \alpha_{i,j} \leq 1 \tag{11}$$

$$0 \leq \beta_{i,k} \leq 1 \tag{12}$$

$$\sum_{j \in RDCT} \alpha_{i,j} V_j = 0 \tag{13}$$

$$\sum_j \alpha_{i,j} V_j PTDF_{i,j} + \sum_k \beta_{i,k} T_k PSDF_{i,k} = \max\left(0, F'_{b,i} - max\left(F_{max,i}\,,\, F_{a,i}\right)\right) \tag{14}$$

with

c_i	Share of total costs of all XRAs attributed to XNEC *i* [€]
r_i	Relative weight of XNEC *i* in cost sharing
C^{all}	Total costs of all XRAs equal to $\sum_j C_j$ [€]
$\alpha_{i,j}$	optimisation variable representing a fraction of optimal volume V_j of XRA *j* determined by coordination optimisation which is needed to solve the congestion on XNEC *i*
$\beta_{i,k}$	optimisation variable representing a fraction of the T_k determined by coordination optimisation which is needed to solve the congestion on XNEC *i*
C_j	Total cost or revenue of applied XRA *j* [€]
V_j	The optimal volume of XRA *j* determined by coordination optimisation [MW]

T_k	The optimal change of tap of XRA *k* (consisting of PSTs), which is the difference between the tap of this XRA before the coordination optimisation and the optimal tap determined by coordination optimisation [unit]
$PTDF_{i,j}$	Power transfer distribution factor describing the impact of a change of 1 MW of XRA *j* on the physical flow on XNEC *i*
$PSDF_{i,k}$	Phase shifting distribution factor describing the impact of a change of 1 tap position of PST *k* on the physical flow on XNEC *i* [MW]
$F'_{b,i}$	Total flow on XNEC *i* calculated before coordination optimisation adjusted for the relieving impact of applied non-costly XRAs, except PSTs [MW]
$F_{max,i}$	Maximum flow on XNEC *i* [MW]
$F_{a,i}$	Total flow on XNEC *i* calculated after coordination optimisation that includes the impact of all XRAs [MW]

The following additional rules shall apply for the calculation of variables:

a) If C^{all} is positive/negative and less than half of relative weights r_i of XNECs are lower/higher than 0, these weights shall be set to 0 before applying the Equation 8;

b) If C^{all} is positive/negative and half or more of relative weights r_i of XNEC *i* are lower/higher than 0, the positive/negative value of the lowest/highest negative/positive weight shall be added to all weights of all XNECs before applying the Equation 8;

c) If C^{all} is positive/negative and all relative weights r_i of XNEC *i* are 0, new weights shall be calculated and shall be equal to the right side of Equation 14; and

d) In case the right side of the Equation 14 is higher than the left side of this equation when all $\alpha_{i,j}$ and $\beta_{i,k}$ are set to 1, the former shall be set equal to the latter.

7.2 Formula fairness

The SEW based on the solution of the nodal optimization is computed as :

$$SEW_{z,n} = \sum_{n \in z} C.S._{n} + P.S._{n} + \sum_{L \in z} C.R._{L,n} + 0.5 * \sum_{L \in bord..z} C.R._{L,n} \quad (15)$$

With

- $C.S._{n} = L_n * (\rho_n - VoLL)$
- $P.S._{n} = P_g * (\rho_{n(g)} - \varphi_g)$

- $C.R._{L,n} = F_{L(n1,n2)} * (\rho_{n1} - \rho_{n2})$
- ρ_n : marginal price at node n
- φ_g: production cost of generator g
- L_n : load at node n
- P_g : production of generator g
- F_L : flow on line L

The SEW based on the solution zonal approach is computed as :

$$SEW_{z,z} = C.S._z + P.S._z + \sum_{L \in z} C.R._{L,z} + 0.5 * \sum_{L \in bord..z} C.R._{L,z} - Redispatch_z \quad (16)$$

With

- $C.S._z = L_z * (\rho_z - VoLL)$
- $P.S._z = P_g * (\rho_{z(g)} - \varphi_g)$
- $C.R._{L,z} = F_{L(z1,z2)} * (\rho_{z1} - \rho_{z2})$
- ρ_z : marginal price for zone z
- φ_g : production cost of generator g
- L_z : load of zone z
- P_g : production of generator g
- F_L : flow on line L

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