Study on technical and legal definitions of congestions in electricity networks

Final report

Prepared for: European Union Agency for the Cooperation of Energy Regulators (ACER)

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1. Introduction

The regulatory and legal framework around the EU power system has numerous implications on the technical and economic performances of the sector. An important aspect of this framework relates to congestions. Regulation (EU) 2019/943 of the European Parliament and the Council of 5 June 2019 on the internal market for electricity (Electricity Regulation) and Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (CACM Regulation) laid down the following definitions of different types of congestions:

- Electricity Regulation Article 2(4): ‘congestion’ means a situation in which all requests from market participants to trade between network areas cannot be accommodated because they would significantly affect the physical flows on network elements which cannot accommodate those flows;
- CACM Regulation Article 2(18): ‘physical congestion’ means any network situation where forecasted or realised power flows violate the thermal limits of the elements of the grid and voltage stability or the angle stability limits of the power system;
- CACM Regulation Article 2(17): ‘market congestion’ means a situation in which the economic surplus for single day-ahead or intraday coupling has been limited by cross-zonal capacity or allocation constraints;
- Electricity Regulation Article 2(6) ‘structural congestion’ means congestion in the transmission system that is capable of being unambiguously defined, is predictable, is geographically stable over time, and frequently reoccurs under normal electricity system conditions;

Although the above definitions may be suitable when looking at them individually, they are inadequate for two reasons:

- The definition of a structural congestion is not clear, because it lacks clearer definitions of frequency, predictability and stability as well as the clarity whether it applies separately to congestion defined in the Electricity Regulation or physical congestion defined in the CACM Regulation;
- The links between the first three definitions are subject to interpretation. In particular, the relationship between congestion and physical congestion is not clear in a way that would unambiguously link one congestion to the other. This is because the definition of congestion in the Electricity Regulation (i) does not refer to physical congestion explicitly but rather only implicitly and (ii) refers to a significant impact on physical congestion without specifying any threshold defining when the impact is significant.

In that context, this project aims (i) at clarifying concepts related to congestions in power systems (including the interdependences between the various kinds of congestions), (ii) at defining clear boundaries between structural and non-structural congestions, and at (iii) providing advice on legal/regulatory changes that would be required to be able to unequivocally identify the various kinds of congestions.

In order to reach these objectives, this report will be structured as follows. Chapter 2 will review and analyze existing definitions related to congestions in power systems. On that basis, Chapter 3 will propose improved definitions, to ease their applicability. Then, Chapter 4 will define methodologies to identify and characterize congestions, in particular to distinguish structural and non-structural congestions, and will demonstrate the applicability of these methodologies. Chapter 5 will subsequently provide advice on legal/regulatory changes needed for the applications on the methodologies proposed in this report. Finally, Chapter 6 will conclude and will provide recommendations on the way forward.

2. Review of existing definitions

The first step of this project consists in developing a solid understanding of the existing concepts related to congestions, in order to build on such understanding for the application of concepts and for the clarification of definitions if need be. This is the purpose of this Chapter. As this project deals with the European electric power system, Section 2.1 will first analyse the EU framework. However, in order to challenge European definitions and to bring an additional perspective, it appears important to analyse international definitions, outside Europe, in Section 2.2. Finally, Section 2.3 will provide a discussion about EU definitions, based on prior analyses, in order to pave the way for possible improvements.

2.1 EU framework

Although reference definitions at the EU level are now the ones of the CACM Regulation and of the Electricity Regulation (as mentioned in the introduction of this report), an analysis of the origin of these definitions throughout the successive EU energy packages can help to properly understand them. Subsection 2.1.1 aims to provide such an analysis. Then, Subsection 2.1.2 will propose an interpretation of these definitions.

2.1.1 Definitions in the EU energy packages

The EU's approach to congestion management has been motivated by a desire to provide non-discriminatory and transparent access to transmission capacity while simultaneously promoting the efficient and secure operation of the internal electricity market. In response to these policy objectives and the shifting dynamics of the EU electricity sector, the legal definition of electricity congestion has evolved in time.

This subsection aims at providing insights into the development of the definitions of "congestion" as defined in the CACM Regulation and Electricity Regulation.

Congestion was not given significant focus during the initial phases of EU energy policy. Concerns regarding congestion, particularly regarding cross-border transmission capacity, emerged when the EU started to support the growth of a single electricity market.

The first energy package of 1996 contained two directives, among which the **Electricity Directive**[1]. This Directive did not focus on congestion, its aim being to encourage the growth of a single energy market, to ensure that all customers are free to purchase electricity from the supplier of their choice and to set uniform regulations for the generation, transmission, and distribution of power.

The second energy package of 2003 contained two Directives and one Regulation. The **2003 Electricity Directive**[2] and its preparatory documents barely made mentions of "congestion". In the text of the initial version of the Directive itself, congestion was mentioned in relations to the rules around getting access to the grid and the conditions under which a TSO/DSO was allowed to refuse such access, as the only way to manage congestion at the time was to refuse access to the grid.

However, as a result of the opening of the electricity market allowing free choice of supplier for wholesale consumers, the Commission recognized the emerging need to deal with congestion issues in and between national transmission systems [3]. This need arose from increased demand and cross-border trade.[4] Notably, in 2000, the first cross-border auctions were organized on the Dutch borders by TSO Auction, marking a significant development. In response to these changes, **Regulation 1228/2003 on conditions for access to**

[1] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity

[2] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC - Statements made with regard to decommissioning and waste management activities OJ L 176, 15.7.2003, p. 37–56

[3] Communication from the Commission to the Council and the European Parliament - Completing the internal energy market, COM/2001/0125 final

[4] Communication from the Commission to the Council and the European Parliament - Completing the internal energy market, COM/2001/0125 final

the network for cross border exchanges in electricity[5] provided rules on congestion management and introduced for the first time a definition of "*congestion*":

"'congestion' means a situation in which an interconnection linking national transmission networks, cannot accommodate all physical flows resulting from international trade requested by market participants, because of a lack of capacity of the interconnectors and/or the national transmission systems concerned;"[6]

In 2006, the Commission amended **Regulation 1228/2003** to include an Annex 1 on **Guidelines on the management and allocation of available transfer capacity of interconnections between national systems**[7]. The introduction of these guidelines stemmed from the consideration by the Commission that efficient methods of congestion management should be introduced for cross-border electricity interconnection capacities to ensure effective access to transmission systems for the purpose of cross-border transactions. The Guidelines establishes general principles for TSOs to follow, including accommodating cross-border transactions, minimizing restrictions on interconnections when there's no congestion, and ensuring congestion management methods promote competition and economic efficiency. **Structural congestion** is mentioned in the guidelines as a situation where appropriate congestion management rules and arrangements must be implemented immediately by TSOs. The congestion management methods (market-based) outlined in the Guidelines aim to ensure that physical power flows associated with allocated transmission capacity comply with network security standards. The Guidelines further provides provisions for coordination between TSOs, timelines for capacity allocation, nomination of transmission rights, and intra-day allocations, transparency, and use of congestion incomes.

The European Parliament tried to include the following mention in its amendments (in bold) *""congestion" means a situation in which an interconnection linking national transmission networks,* ***or within the transmission networks in question****, […]"* to take into account that congestion can also arise within the transmission networks on either side of the interconnections.[8]

The EU third energy package contained two Directives and three Regulations. the updated version of the Electricity Directive, the **2009 Electricity Directive**[9] acted as a crucial component of the internal power market and was the first substantial legislation to handle congestion in the EU. Although "*congestion management*" was mainly added by the directly applicable Annex 1 to Regulation 1228/2003 and its updated version, **Regulation 714/2009**[10], the 2009 Electricity Directive provided for the monitoring of congestion management of national electricity system by the regulatory authorities. To that end, the 2009 Electricity Directive obliged TSOs to submit their congestion management rules, including capacity allocation, to the national regulatory authorities (Art. 37 (9)). Further, the 2009 Electricity Directive provided that each TSO had to be responsible for granting and managing (third-party) access to cross-border transmission, including the collection of congestion rents.

Under the third energy package, the definition of congestion as found in Regulation 1228/2003 was included in **Regulation 714/2009.** No further explanation in the preparatory documents of the EU was however given on how the Member States reached this definition.

Regulation 714/2009 took into account that congestions between national networks are affected by internal capacity as its article 16.3 provides that the maximum capacity of the interconnections and/or the transmission networks affecting cross-border flows must be made available to market participants.

Annex 1 of Regulation 1228/2003 on the management and allocation of available transfer capacity of interconnections between national systems was annexed to Regulation 714/2009, with minor differences in the text compared to its previous version with Regulation 1228/2003.

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[5] Regulation (EC) 1228/2003 of the European Parliament and of the Council of 26 June 2003 on conditions for access to the network for cross-border exchanges in electricity, OJ L 176, 15.7.2003, p. 1–10
[6] Regulation (EC) 1228/2003 on conditions for access to the network for cross border exchanges in electricity, Art. 2 (2) (c).
[7] 2006/770/EC: Commission Decision of 9 November 2006 amending the Annex to Regulation (EC) No 1228/2003 on conditions for access to the network for cross-border exchanges in electricity, OJ L 312, 11.11.2006, p. 59–65.
[8] Report on the proposal for a European Parliament and Council regulation on conditions for access to the network for cross-border exchanges in electricity, (COM(2001) 125 – C5-0185/2001 – 2001/0078(COD)), 28 February 2002
[9] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, OJ L 211, 14.8.2009, p. 55–93
[10] Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003, OJ L 211, 14.8.2009, p. 15–35

Nonetheless, by introducing the idea of "congestion management procedures" (CMPs) and mandating TSOs to design and execute CMPs in collaboration with other TSOs, the 2009 Third Energy Package advanced the EU's approach to congestion. To further coordinate cross-border congestion management, the Package also introduced the idea of regional electricity markets.

Pursuant to the network code development process provided in Article 6 of Regulation (EC) 714/2009, the **CACM Regulation**[11] that establishes a guideline on capacity allocation and congestion management was developed in cooperation with ENTSO-E, ACER and with inputs from other stakeholders.

In 2011, the ACER developed Framework Guidelines on CACM for Electricity[12]. The Framework Guidelines aimed at setting out clear and objective principles for the development of network codes pursuant to Article 6 of Regulation 714/2009. The Framework Guidelines complemented, where necessary, Annex 1 to the Regulation 714/2009 and specified the detailed aspects which need to be implemented in the network codes.

Based on the ACER Framework Guidelines, and following the Commission request that ACER start drafting the network code,[13] ENTSO-E developed the Network Code on Capacity Allocation and Congestion Management ("Network Code")[14] and submitted the Network Code to the ACER on 27 September 2012. Applicable to TSOs, NRAs, the ACER, and designated nominated electricity market operators and market participants, the Network Code sets common rules for capacity allocation and managing cross bidding zone congestion in the day Ahead and intraday markets. The Network Code provided for a definition of "market congestion", "physical congestion", and "structural congestion":

"Market Congestion means a situation in which the Economic Surplus has been limited by the Cross Zonal Capacity or other active Allocation Constraints;

Physical Congestion means any network situation, either described in a Common Grid Model, or occurring in real time, where power flows has to be modified to respect Operational Security;

Structural Congestion means congestion in the Transmission System that: can be unambiguously defined; is predictable; is geographically stable over time; and is frequently reoccurring under common circumstances;"[15]

On 19 December 2012, the ACER adopted an opinion[16] on the Network Code, inviting ENTSO-E to address the specific concerns expressed in the opinion and to resubmit an amended Network Code to the ACER. On 8 February 2013, ENTSO-E informed the Agency that, in the interest of delivering the Internal Energy Market as quickly as possible, it will not be using its right to resubmit the Network Code.[17]

On 14 March 2013, the ACER adopted a recommendation[18] to the Commission to adopt the Network Code, provided that specific amendments proposed by the ACER were made.

Based on the ACER recommendation, the European Commission revised the Network Code, which was then finally adopted as a Commission guideline in July 2015 and entered into force on 14 August 2015. The CACM Regulation supplements Annex I of Regulation 714/2009, in accordance with the principles set out in Article 16 of Regulation 714/2009, and . In accordance with Article 18(3) of Regulation 714/2009, the Commission must consult the Agency, ENTSO-E and other relevant stakeholders, before proposing any amendment to the CACM Regulation.

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[11] Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management, OJ L 197, 25.7.2015, p. 24–72

[12] ACER, Framework Guidelines on Capacity Allocation and Congestion Management for Electricity, FG-2011-E-002, 29 July 2011

[13] European Commission, Invitation to start the procedure on a framework guideline on electricity grid connection rules, ENER/B2/TOB/mta/s1065637, 16 September 2011

[14] European Network of Transmission System Operators for Electricity, Network Code on Capacity Allocation and Congestion Management, 27 September 2012.

[15] European Network of Transmission System Operators for Electricity, Network Code on Capacity Allocation and Congestion Management, 27 September 2012, article 2.

[16] ACER, Opinion of the Agency for the Cooperation of Energy Regulators No. 10/2012 on ENTSO-E's Network Code on Capacity Allocation and Congestion Management, 19 December 2012.

[17] ACER, Recommendation of the Agency for the Cooperation of Energy Regulators No.01/2013 on the Network Code on Capacity Allocation and Congestion Management, 14 March 2013, p. 2.

[18] ACER, Recommendation of the Agency for the Cooperation of Energy Regulators No.01/2013 on the Network Code on Capacity Allocation and Congestion Management, 14 March 2013.

The CACM Regulation contains three definitions of congestion for “market” congestion, “physical” congestion, and “structural” congestion.

p“17. ‘market congestion’ means a situation in which the economic surplus for single day-ahead or intraday coupling has been limited by cross-zonal capacity or allocation constraints;

18. ‘physical congestion’ means any network situation where forecasted or realised power flows violate the thermal limits of the elements of the grid and voltage stability or the angle stability limits of the power system;

19. ‘structural congestion’ means congestion in the transmission system that can be unambiguously defined, is predictable, is geographically stable over time and is frequently reoccurring under normal power system conditions;”[19]

Very few information is also available on how these definitions were reached, whether on the EU website (*eur-lex*) or in the documents provided by ENTSO-E on the history and development of the CACM Regulation (stakeholders group meetings and workshops, presentations, draft CACM Regulation, etc.)[20]. For structural congestion, the updated draft of the ENTSO-E following consultation of the Network Code on Capacity Allocation and Congestion Management[21] informs that congestion can be defined as structural if it does not change its geographic position in the network **under short-term influences**:

“*Structural Congestion - congestion in the grid that:*

- *can be unambiguously defined;*
- *is predictable;*
- *is stable over time, i.e. does not change its geographic position in the network under short-term influences; and*
- *is frequently reoccurring under common circumstances.”*[22]

The Fourth Energy Package of 2019 consists of one Directive and three RegulationsThe definition of “congestion” included in **Regulation 2019/943 on the internal market for electricity (recast)**[23] moved on from the one of Regulation 1228/2003 to:

“*a situation in which all requests from market participants to trade between network areas cannot be accommodated because they would significantly affect the physical flows on network elements which cannot accommodate those flows;”*[24]

Further, **“structural” congestion** was defined as such by the Electricity Regulation:

“‘structural congestion’ means congestion in the transmission system that is capable of being unambiguously defined, is predictable, is geographically stable over time, and frequently reoccurs under normal electricity system conditions;”[25]

Although the rationale behind these definitions itself is not straightforwardly given in the preparatory documents of the Electricity Regulation, the preparatory documents of the fourth energy package, as well as the Electricity Regulation itself, provide a few insights into the preoccupation of the EU with regards to congestion, and especially structural congestion.

For example, the Commission Staff Working Document on the fourth energy package put emphasis on the benefits of price zone boundaries that reflects structural congestion.[26] According to the same document, linking structural congestion to the configuration of bidding zones would mitigate issues linked to investments,

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[19] CACM Regulation, Art. 2.
[20] ENTSO-E, Capacity Allocation & Congestion Management https://www.entsoe.eu/network_codes/cacm/
[21] European Network of Transmission System Operators for Electricity, Network Code on Capacity Allocation and Congestion Management Updated Draft Following Consultation, 16 July 2012
[22] European Network of Transmission System Operators for Electricity, Network Code on Capacity Allocation and Congestion Management Updated Draft Following Consultation, 16 July 2012, p. 12
[23] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast), OJ L 158, 14.6.2019, p. 54–124.
[24] Regulation 2019/943, Art. 2 (4)
[25] Regulation 2019/943, Art. 2 (6)
[26] Commission Staff Working Document, SWD(2016) 410 final, Part 4/5, 30.11.2016, https://eur-lex.europa.eu/resource.html?uri=cellar:e4c834ae-b7b8-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF, p.230.

loop flows[27] and redispatching costs. The Electricity Regulation itself refers to the CACM and states that bidding zones should be defined in a manner to ensure market liquidity, efficient congestion management and overall market efficiency.28 Further, the Electricity Regulation states that, in order to ensure efficient operation and planning of the Union electricity network and to provide effective price signals for new generation capacity, demand response and transmission infrastructure, bidding zones should reflect structural congestion.[29] The Electricity Regulation further provides that, in order to address congestion and optimize bidding zones without jeopardising liquid markets and grid, Member States should be able to either choose between a reconfiguration of their bidding zone or implement measures such as grid reinforcement and grid optimization.[30]

The EU current definitions are thus highly influenced by the need of optimizing bidding zones. Any further modifications of these definitions will thus need to take this concern into account.

2.1.2 Interpretation of the EU definitions

Following this description of definitions, a development of a solid interpretation of the concepts defined by the CACM Regulation and by the Electricity Regulation related to congestions is required, in order to build on such interpretation for the improvement and clarification of ambiguous aspects. Hence, this subsection provides a detailed description of our understanding of the different definitions. In particular, in our opinion, as we will show here, the CACM Regulation definitions have been established with the concept of a zonal market with redispatch in mind, while the Electricity Regulation definition is more general, although the Electricity Regulation is also based on zonal markets. The different market steps to which the text refers, are shown in Figure 2-1.

On the one hand, the CACM Regulation definition of "**physical congestion**" mentions the **violation** of thermal limits of elements of the grid or of voltage/angle stability limits (i.e., violation of operational security limits, as defined also by the CACM Regulation). Therefore, if we refer to the violation of operational security limits by forecasted power flows, it mainly concerns the grid constraints not directly considered for the capacity allocation (market clearing), as a violation of operational security limits are not supposed to happen if these constraints are enforced within the market coupling algorithm[31].. This means that such type of congestion cannot be spotted systematically based on forecasted power flows on cross-border lines and Critical Network Elements (CNEs) included in the set of constraints of the market optimization, while they can be identified on all the remaining network elements by means of ex-post computations. Moreover, due to forecast errors, realised power flows might nevertheless violate operational security limits on transmission elements considered. Furthermore, the reference to "forecasted" power flows does not point explicitly to a specific step of the market process, thus opening the door to **different interpretations about criteria to identify this type of congestion**. Indeed, it could be claimed that physical congestions may be spotted already after the capacity calculation process: cross-border capacity parameters are computed on the basis of a common grid model and this information could be used as input to estimate flow in all the remaining network elements and identify physical congestions. Analogously, physical congestions could be identified after the capacity allocation process, i.e., when power flows in the European electric power systems are estimated based on the results of the market clearing. These congestions must then be considered in the redispatch process (or, more generally, in the determination of remedial actions), in order to ensure the reliable operation of the grid. Finally, overloads may arise in real time and be considered as physical congestions, too, and must be relieved as well by redispatching or other remedial actions. Note that this interpretation is confirmed by the CCR Core TSOs' proposal for a common methodology for coordinated redispatching and countertrading, as it defines redispatching as "a measure performed by one or several TSOs [...] in order to [...] relieve physical congestions"[32]. In summary, the definition of physical congestion mentions the violation of operational security

[27] Phenomenon whereby energy will flow around the congestions through another zone, against market price signals.
[28] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast), OJ L 158, 14.6.2019, p. 54–124, recital 19.
[29] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast), OJ L 158, 14.6.2019, p. 54–124, recital 30.
[30] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast), OJ L 158, 14.6.2019, p. 54–124, recital 31.
[31] Note that it is true if the available transmission capacity has not been artificially increased to meet the minimum capacity requirement of 70%. If not, some transmission constraints can be nevertheless violated.
[32] CCR Core TSOs' Cooperation, "Common methodology for coordinated redispatching and countertrading for the Core CCR in accordance with Article 35(1) of Commission Regulation (EU) 2015/1222 of 24 July 2015," 22 February 2019

limits, which should happen if constraints on the network elements are enforced in the observed market step (either capacity calculation or capacity allocation), as long as the available transmission capacity has not been artificially increased to meet the minimum capacity requirement of 70%. Hence, they can be identified either through ex-post computations on the remaining network elements ("*forecasted power flows*") or as actual unpredicted violations in real time ("*realised power flows*").

The CACM Regulation also provides the definition of "**market congestion**" which mentions the limitation of economic surplus by **cross-zonal capacity (flow-based parameters or NTC values) or allocation constraints**. Hence, it refers to grid constraints directly considered at the level of market coupling (the economic surplus is limited by grid constraints, which implies that grid constraints are binding but not violated). Therefore, this type of congestion is identified through the capacity allocation process: it corresponds to binding constraints in the market clearing algorithm. The CACM Regulation does not provide an explicit relationship between the definitions of market congestion and of physical congestion, which again opens the door to different interpretations. Given above, one interpretation could consider that a market congestion is directly caused by a physical congestion but might be related to physical congestion (e.g., binding network element in capacity calculation or allocation which appears in fine violated due to forecast errors), and that a large part of physical congestions are not related to market congestions (e.g., physical congestions on network elements not considered in the market coupling algorithm).

On the other hand, the definition of **congestion** in the Electricity Regulation does not distinguish congestions managed at the level of the market coupling algorithm and congestions managed ex-post through redispatch, as it just states that a congestion occurs when the grid cannot accommodate the flows resulting from all requests from market participants for trades between at least two network areas. In our opinion, it implies that what is called "congestion" by the Electricity Regulation comprises both market congestions and network congestions. Indeed, both types of congestions limit the efficiency of the market and are triggered by constraints on physical flows. Hence, this **definition appears as very broad, and ambiguous**, as it does not refer to a specific market step. Moreover, it makes reference to unspecified areas and their related trade, without setting any geographical and/or technical boundary.

We can conclude that market congestions, which reveal themselves as outcome of the capacity allocation process in the form of active constraints, can be automatically considered as congestions. After the capacity allocation process (market clearing), TSOs verify the flows inside the bidding zones (in N and in N-1 conditions) and spot the presence of physical congestions to be eliminated (or resolved) by means of remedial actions (including redispatch). It might happen that, following remedial actions (and, thus, in real time), lines that appeared as physically congested in the post capacity allocation phase would be characterized by a flow well below their technical limit if other elements are more constraining. These lines would not be considered as congestions in real time because, according to the definition in the Electricity Regulation, we cannot consider that the lines would not be able to accommodate additional flow. On the contrary, physical congestions at the lines that operate in real time at their technical limit (binding constraint in the optimization of remedial actions) would be considered as congestions.

The figure below summarizes our interpretation of the definitions of congestions. As shown, depending on the approach, the capacity calculation phase could already allow to get a sense which lines could be congested in later phases[33]. The market clearing allows to acknowledge market congestions and then forecast the physical congestions. Finally, physical congestions may arise in real time. These concepts are illustrated on a small network in Appendix 7.1.

Given the absence of explicit reference to market steps in the definitions, Figure 2-1 only represents one of the possible interpretations of the definitions and their interdependencies. This highlights the **need to improve clarity** and provide clear boundaries around the different congestion definitions, in order to be able to build suitable methodologies to identify them correctly. This is pivotal to then act on the issue with long-lasting solutions; however, currently there is **no clear definition that tackles the root causes of congestions**, focusing instead on the ultimate impacts on the network.

[33] For instance, if the base case used to calculate the cross-border transmission capacity available to market participants is based on a (security-constrained) optimal power flow, binding constraints will correspond to congestions.

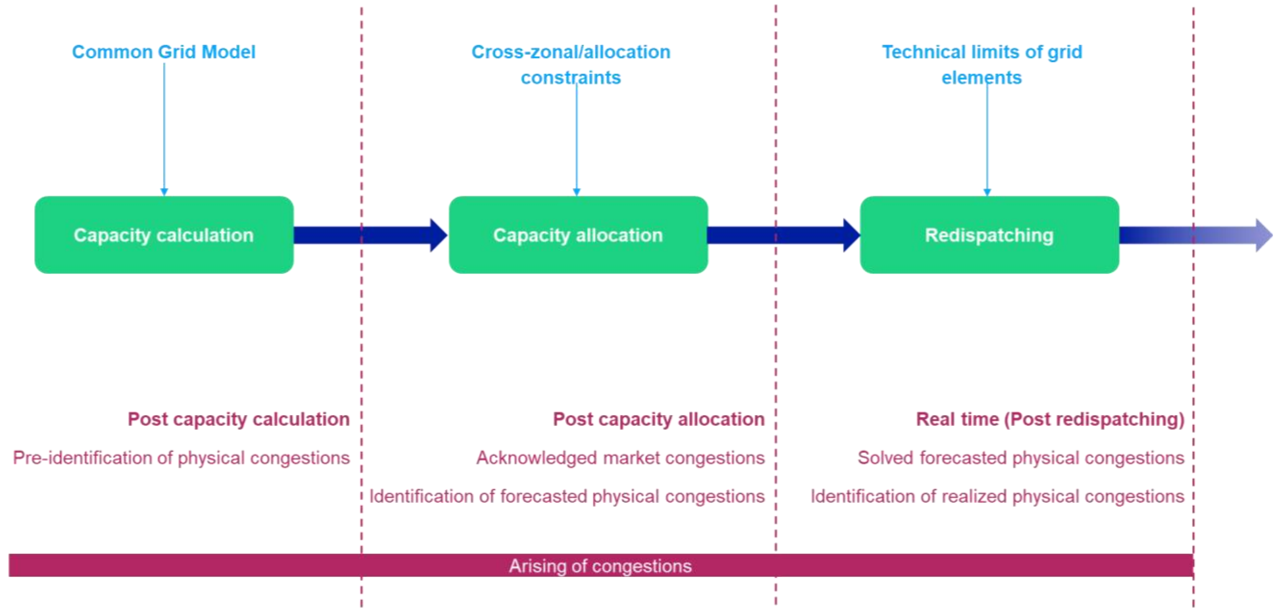

Figure 2-1: Our interpretation of CACM Regulation and Electricity Regulation congestion definitions

2.2 International definitions

2.2.1 On a general note on congestion

In countries outside the EU, electricity congestion is a common occurrence due to a variety of factors. For example, countries relying on one variable energy power source (e.g., hydroelectricity) may face congestion during dry seasons, while countries with inadequate infrastructure may be unable to accommodate the growing demand for electricity. Other causes of congestion may be insufficient investment in renewable energy and natural disasters.

In Africa, for example, electricity congestion is a major issue, with many countries experiencing power shortages and blackouts on a regular basis. According to the World Bank, more than 600 million people in sub-Saharan Africa lack access to reliable electricity, and the situation is likely to worsen as the population grows and the demand for energy increases.[34]

In Asia, electricity congestion is also a common problem, particularly in densely populated countries such as India and China. This contributes to the rise of blackouts, often also caused by limitations in the generation portfolio that cannot meet demand. In India, for example, power outages are a regular occurrence, and the country has been investing heavily in renewable energy sources such as solar and wind power to address the issue.[35]

In Latin America, electricity congestion is a significant challenge as well, particularly in countries that rely heavily on hydroelectric power. In Brazil, for example, the electricity grid is hydroelectricity-based and is often strained during periods of drought when water levels in dams drop, causing not only shortages and blackouts,[36] but also huge differences in spot prices between the zonal areas of the country.[37]

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[34] "Sub-Saharan Africa: Access to Electricity (% of population)." World Bank Data. The data is presented as a percentage of the population that has access to electricity, and it indicates that access to electricity in the region is significantly lower than the global average. Available online at https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG

[35] Prasanth Regy, Rakesh Sarwal, Clay Stranger, Garrett Fitzgerald, Jagabanta Ningthoujam, Arjun Gupta, Nuvodita Singh. 2021. *Turning Around the Power Distribution Sector: Learnings and Best Practices from Reforms*. NITI Aayog, RMI, and RMI India. Available online at https://www.niti.gov.in/sites/default/files/2021-08/Electricity-Distribution-Report_030821.pdf

[36] Argus Media, *Brazil lacks power shortage plan, risks blackouts*, 18th June 2021 https://www.argusmedia.com/en/news/2226420-brazil-lacks-power-shortage-plan-risks-blackouts

[37] F. Porrua, G. B. Schuch, L. A. Barroso, A. Street, M. Junqueira, S. Granville, *Assessment of transmission congestion price risk and hedging in the Brazilian electricity market,* CIGRE/IEEE PES, Conference Paper , November 2005 *https://www.researchgate.net/publication/4188078_Assessment_of_transmission_congestion_price_risk_and_hedging_in_the_Brazilian_electricity_market*

In the Middle East, electricity congestion is often the result of political instability and conflict. In Iraq, for example, power outages are a common occurrence due to sabotage of the country's power grid by insurgents and other armed groups.[38]

In North America, electricity congestion is primarily an issue in densely populated areas such as California and New York,[39] where the demand for electricity is high and the infrastructure is aging. In recent years, these regions have experienced a number of power outages and brownouts due to heatwaves and other weather-related events.[40]

2.2.2 Specific information per-country

In **Australia**, which uses zonal pricing, the final report of June 2008 of the Australian Energy Market Commission on congestion management defined congestion in the following way:

"Congestion" is what happens when there is a bottleneck somewhere on this network. That is, whenever a particular element on the network (e.g. a line or transformer) reaches its limit and cannot carry any more electricity than it is carrying already, it is "congested". The flow of power across the network means that when a limit is reached on one part of the network, adjustments have to be made in generation and consumption across the network to ensure that the limit is not exceeded.

In technical terms, congestion places network constraints on dispatch. It interferes with the market's dispatch objective of meeting demand at the lowest possible cost. (In the absence of congestion, electricity to meet demand is supplied by the lowest cost generators; when congestion arises this may not be feasible, so higher-cost generators may have to be dispatched instead.) This introduces risks for the market, which consequently affects bidding, dispatch, pricing, contracts, and risk management, as well as long-term investment decisions"[41]

No legal definition can be found in the National Electricity Law (NEL) or the National Electricity Rules (NER), both enforced by the Australian Energy Regulator (AER).

However, in the NER, when a market participant seeks to move from one of the energy market regions of the country to another due to congestion issues, the participant must issue an application demonstrating the existence of this congestion problem. The NER specifies that a "congestion problem" is then to be identified as follow:

"A region change application must demonstrate, with supporting economic analysis:

(a) that there is a problem with the existing region configuration;

(b) that the problem is attributable to the presence of material and enduring network congestion; and

(c) that the problem has or will detract materially from economic efficiency."[42]

The AER is responsible for monitoring and managing congestion in the National Electricity Market (NEM), which spans the eastern and southern states of Australia. In its 2013 Report on the impact of congestion on bidding and inter-regional trade in the NEM, the AER defines congestion as occurring *"when the incremental increase in the amount of electricity that can flow over a particular line or other transmission system element is constrained by physical or system limitations. These limitations usually reflect the ratings of transmission equipment (generally referred to as 'lines' in this report). The ratings of transmission lines are not always constant and are affected by ambient weather conditions."*[43]

In the **United States**, which uses nodal pricing, although no legal definitions were found by the Consultant in laws and rules, the Federal Energy Regulatory Commission's (FERC) glossary takes an economic (or

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[38] « Protesters block roads in Iraq after third day of power cuts » Samya Kullab, 8 August 2022 – available online at https://apnews.com/article/middle-east-iraq-power-outages-heat-waves-muqtada-al-sadr-b2fe2bd99e7995f31f731bcbbc67c3ad
[39] The U.S. Department of Energy – National Electric Transmission Congestion Study, September 2020, available online at https://www.energy.gov/oe/articles/2020-national-electric-transmission-congestion-study
[40] Storms batter aging power grid as climate disasters spread by M. Brown and others, 6 April 2022, available online at https://apnews.com/article/wildfires-storms-science-business-health-7a0fb8c998c1d56759989dda62292379
[41] Australian Energy Market Commission, Congestion Management Review – Final Report, June 2008, https://www.aemc.gov.au/sites/default/files/content/ed17404e-3a72-491f-a579-b92aaddace36/Final-Report.PDF, p. 7
[42] AEMC, National Energy Rules, clause 2A.2.2
[43] AER, *Special report - The impact of congestion on bidding and inter-regional trade in the NEM*, https://www.aer.gov.au/wholesale-markets/performance-reporting/special-report-the-impact-of-congestion-on-bidding-and-inter-regional-trade-in-the-nem, p. 3

market)-oriented approach and defines congestion as "*a characteristic of the transmission system produced by a constraint on the optimum economic operation of the power system, such that the marginal price of energy to serve the next increment of load, exclusive of losses, at different locations on the transmission system is unequal*. "[44]

The U.S. differentiate between "*transmission constraints*" and "*transmission congestion*". "*Transmission constraints*" is to be understood as the "*physical limits on the amount of electricity flow the system is allowed to carry in order to ensure safe and reliable operation*", while "*transmission congestion*" is to be understood in relation with the economic impacts of congestion on electricity users due to the operation of the system within transmission constraints[45].

"Transmission constraints and transmission congestion are closely related but are different concepts. Transmission constraints are physical limits on the amount of electricity flow the system is allowed to carry in order to ensure safe and reliable operation. Transmission congestion refers to the economic impacts on the users of electricity that result from operation of the system within these limits.

The term "transmission constraint" may refer to:

1. An element of the transmission system, e.g., an individual piece of equipment, such as a transformer, or a group of closely related pieces, such as the conductors that link one substation to another, that limits power flows in order to avoid an overload that could cause one or more elements to fail and thereby jeopardize reliability; or

2. An operational limit imposed on an element or group of elements to ensure that the system, as a whole, will continue to operate reliably following the failure of one or more elements."[46]

"Transmission constraints" is thus used in the U.S. to describe the limitations and restrictions associated with the transportation of electricity through the power grid. This concept aligns closely with the European Union's usage of "Operational Security limits". Both of these terms represent the maximum capacity that a transmission system can handle. Meanwhile, "Transmission congestion" is a term used specifically in the US to denote a situation where demand for power transmission in a particular location or node exceeds the capacity of the transmission system. This results in difficulties in transferring power from one area to another. In Europe, the parallel terminology is "Physical congestion" and "Areal congestion". These terms reflect the same underlying issue of demand surpassing transmission capacity but with an added spatial component, signifying that these limitations can occur within a specific geographical region or across a wider area.

In the **state of California**, the legal definition of electricity congestion is defined by the California Independent System Operator (CAISO), which operates the power grid for most of the state. According to CAISO, "*congestion*" is "*a characteristic of the transmission system produced by a binding Transmission Constraint*[47] *to the optimum economic dispatch to meet Demand such that the LMP*[48]*, exclusive of Marginal Cost of Losses, at different Locations of the transmission system is not equal."* [49]

To address congestion, CAISO uses market-based mechanisms such as congestion revenue rights (CRRs) and transmission congestion contracts (TCCs), which allow generators and other market participants to hedge against congestion-related costs. CAISO also works with transmission owners and other stakeholders to identify and address congestion issues through transmission planning and investment.

Other definitions may be referred to, such as in Namibia, where the new market design of 2019 defines "*network congestion*" as "*a shortage of network capacity resulting in the curtailment of generation supply and or customer demand."*[50]*,* or in Tunisia, where *"congestion or network constraint"* are both defined as a

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[44] FERC, *Glossary*, https://www.ferc.gov/industries-data/market-assessments/overview/glossary

[45] U.S. Department of Energy, *National Electric Transmission Congestion Study,* September 2020, https://www.energy.gov/oe/articles/2020-national-electric-transmission-congestion-study, p. 5

[46] U.S. Department of Energy, *National Electric Transmission Congestion Study,* September 2020, https://www.energy.gov/oe/articles/2020-national-electric-transmission-congestion-study, p. 5

[47] "*Transmission constraint*" refers to "*Physical and operational limitations on the transfer of electric power through transmission facilities*.", CAISO, Appendix A,1st august 2014, https://www.caiso.com/Documents/AppendixA_Definitions_Aug1_2014.pdf, p. 155

[48] Locational marginal pricing

[49] CAISO, Appendix A,1st august 2014, https://www.caiso.com/Documents/AppendixA_Definitions_Aug1_2014.pdf, p. 20

[50] Government of the Republic of Namibia, Ministry of Mines and Energy, *Electricity Supply Industry – Detailed Market Design,* https://www.ecb.org.na/images/docs/Rules_and_Regulations/MSB/MSB_Detailed_Design_Report.pdf, P. 20

“situation in the power system where the operating safety rules are no longer locally satisfied (e.g.: overload of a line, risk of loss of stability, etc.)”[51].

In **India**, which uses zonal pricing, electricity congestion is governed by the Indian Electricity Grid Code. According to it, congestion means a situation where the demand for transmission capacity or power flow on any transmission corridor exceeds its Available Transfer Capability.[52] Further, in some legal documents from the Central Electricity Regulatory Commission, congestion is defined as a situation where the demand for transmission capacity exceeds the available transfer capability.[53]

2.2.3 States where no legal definition was found

No specific legal definitions were found in the countries of **Canada, Saudi Arabia, and China**. However, in Canada (nodal pricing), the Canadian National Energy Board (NEB), which was previously responsible for regulating the country's electricity sector, before being replaced by the Canadian Energy Regulator (CER), used market-based mechanisms such as capacity auctions and congestion management procedures to address congestion. The CER also implements transmission planning and investment programs to alleviate congestion. Similar mechanisms seem to be used by the Saudi Electricity Company (SEC) (responsible for managing the country's electricity transmission and distribution systems), and the State Grid Corporation of China (SGCC) (responsible for managing the country's electricity transmission and distribution systems).

2.3 Discussion

From the analyses above, we can notice that **congestion can be defined in two different ways**: either (i) it is considered that a congestion occurs when a operational security limit (e.g., thermal capacity of a transmission element) **constrains the economic operation of the power system**, or (ii) it is considered that a congestion occurs when **an operational security limit is violated** (e.g. overloaded transmission element). There is thus a fundamental difference between the two ways, as the first one considers that a limit is reached but is not violated, while the second one considers that a limit is violated. The first category of definitions corresponds to the CACM Regulation definition of market congestion and to definitions applicable in Australia and in the United States of America. The second category of definitions corresponds to the CACM Regulation definition of physical congestion and to definitions applicable in Tunisia and in India. The EU has thus the specificity to mix the two ways, which could create confusion. It is also worth to emphasize that, if an electric power system is reliably operated, which is the case for the European electric power system, the violation of operational security limits in operation should be infrequent. This is why the CACM Regulation definition of physical congestion includes the violation of operational security limits by forecasted power flows. However, as emphasized previously, the concept of forecasted power flows is not defined, which opens the door to many different interpretations. Among the reviewed international definitions, the explicit reference to the concept of forecast is unique to Europe, even though, in the United States, it could be considered that the congestion definition implicitly embeds the notion of forecasting violation of transmission constraints.

Another point of attention regarding the status quo is the confusion that the name of physical congestion itself could entail. Indeed, the name itself connects the concept of congestion to its physical origin, i.e., a system operational security limit linked to grid elements. We could thus intuitively interpret this concept as follows: a physical congestion occurs when operational security limits are either constraining the economic operation of the electric power system or are violated. However, this interpretation is not in line with the interpretation given in Subsection 2.1.2 with the zonal organization of the market in mind: if an operational security limit is constraining the economic operation but not violated, it does not correspond to a physical congestion as defined currently by the CACM regulation.

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[51] Translated to english from the Journal Officiel de la République Tunisienne 14th February 2017, *Order of the Minister of Energy, Mines and Renewable Energy of February 9, 2017, approving the specifications relating to the technical requirements for the connection and evacuation of energy produced from renewable energy facilities connected to the high and medium voltage network (“Arrêté de la ministre de l’énergie, des mines et des énergies renouvelables du 9 février 2017, portant approbation du cahier des charges relatif aux exigences techniques de raccordement et d’évacuation de l’énergie produite à partir des installations d’énergies renouvelables raccordées sur le réseau haute et moyenne tension”)* http://www.steg-er.com.tn/wp-content/uploads/bsk-pdf-manager/2017-05-26_6_15.pdf, P. 664
[52] *Draft Indian Electricity Grid Code*, dated 7 June 2022 - https://cercind.gov.in/2022/draft_reg/Draft-IEGC-07062022.pdf
[53] Central Electricity Regulatory Commission, *Monthly Report on Short-term transactions of Electricity in India*, September 2022 - https://cercind.gov.in/2022/market_monitoring/MMC%20Report%20Sep%202022.pdf

A final point of attention that we could mention is the distinction between structural and non-structural congestions, made in the Electricity Regulation. Same as the definition of congestion given in the Electricity Regulation, the definition of structural congestion describes a general concept, without specifically referring to the type of congestion and whether it applies to capacity calculation, capacity allocation or redispatch phase. Moreover, it attributes several characteristics to the congestion; however, the Electricity Regulation **does not provide any specification on the exact thresholds** to be associated to such features. Furthermore, an implicit idea of location appears to be present behind it, as shown by the definition itself (e.g., “geographically stable”), and by Article 14 of the Electricity Regulation (e.g., “bidding zones shall not contain such structural congestions”), while the definitions of “Congestion”, “Market congestion” and “Physical congestion” given in the CACM Regulation and in the Electricity Regulation allow us to find if there is congestion in an electric power system, but not necessarily to pinpoint the origin of the congestion as the three of them define a congestion as a “situation”. There is thus a gap between them and the concept of structural congestion. Therefore, improved clarity is also necessary regarding that concept.

3. Proposition of improved definitions

As explained in the previous Chapter, although the definitions of "Congestion", "Market congestion", "Physical congestion" and "Structural congestion" given in the CACM Regulation and in the Electricity Regulation constitute a good basis, they have a number of shortcomings, among which ambiguity and unclarity, which could hamper their use in formal processes such as the bidding zone review and the reporting on structural congestions. For that reason, this Chapter proposes to slightly improve them. It is structured as follows. Section 3.1 will detail requirements on the set of definitions needed for congestions. Section 3.2 will then propose a comprehensive set of improved definitions. Finally, Section 3.3 will elaborate on the interdependences between the different concepts behind the definitions.

3.1 Requirements

When reworking the definitions, the following principles should be kept in mind:

- **Limited room for interpretation.** Ambiguity should be avoided as much as possible and, if the door is open for interpretation on specific points, formal definitions should be complemented by a text explaining how to interpret them.
- **Straightforward application.** The way to apply definitions to identify and characterize congestions should be clear and straightforward.
- **Clear relationships between definitions.** Since different aspects of congestions must be targeted, a unique definition for congestions is not viable, and multiple definitions must be used. However, the relationships and possible interdependences between definitions must be clear.

These principles will be used in the next section.

3.2 Set of improved definitions

As explained in Section 2.3, the current definition of physical congestion appears to be the most concerning one, as it does not meet requirements mentioned in the previous Section. In particular, it opens the door to numerous interpretations and various ways to apply it, and the exact relationship with market congestion is unclear. This Section will thus start by proposing an improved version of the definition of physical congestion (subsection 3.2.1). Then, it will propose an improved version of the definition of market congestion (subsection 3.2.2). To bridge the gap between definitions of congestions linked to situations and the need to identify between which areas we have congestions for the identification of structural congestions, a new concept of "areal congestion" will be proposed in subsection 3.2.3 as an update of the general definition given in the Electricity Regulation. Finally, subsection 3.2.4 will propose a slightly reworked definition for the concept of "structural congestion".

3.2.1 Physical congestion

The current definition states that there is a physical congestion if forecasted or realized power flows violate operational security limits. Subsection 2.1.2 discussed the ambiguity behind the concept of forecasted power flows. Section 2.3 also mentioned two different possibilities to define a physical congestion: (i) when a operational security limit constrains the economic operation of the power system, or (ii) when a operational security limit is violated. On that basis, two possible ways to clarify the concept of physical congestion emerge:

- We could consider that there is a physical congestion if one or several grid elements are limiting the total socio-economic welfare (or economic surplus) because a further marginal increase of that welfare would lead to the violation of associated operational security limits, taking into account contingencies;
- We could alternatively consider that there is a physical congestion if one or several grid elements are not able to simultaneously accommodate all requests from market participants to trade electricity (best economic solution disregarding the network constraints) because it would lead to the violation of associated operational security limits, taking into account contingencies.

The two ways will lead to the detection of the same situations of congestion, but the associated grid elements might differ. Indeed, if an incremental increase of the total socio-economic welfare leads to the violation of the operational security limits associated to one or several grid elements, it implies that the accommodation of all requests from market participants to trade electricity would lead to the violation of operational security limits, and vice-versa. Hence, the maximum welfare reachable through trade mechanisms (accommodating all requests from market participants) cannot be achieved because of infrastructure constraints. However, when looking at the limitation to an incremental increase of the socio-economic welfare, only the binding constraints will be relevant, and thus the most constraining elements, while, when looking at the ability of the grid to accommodate all requests from market participants, all constraints violated by the acceptance of such requests will be relevant. It implies that more constraints will be identified following the second way. These concepts are illustrated by means of the simple 2-bus system shown in Figure 3-1, which presents two grid elements in series characterized by different capacities. In particular, the transformer has a capacity of 1400 MW, while the line connecting the transformer and node N2 has a capacity of 1645 MW. In order to maximise the socio-economic welfare, market participants are willing to transfer 2000 MW from N1 to N2. There is obviously a physical congestion. According to the first way to identify physical congestions, only the first element will be relevant [54]: the grid will be able to transfer only 1400 MW, well below the limit of the second element. According to the second way, both elements will be relevant: if we try to transfer 2000 MW, they will be both overloaded.

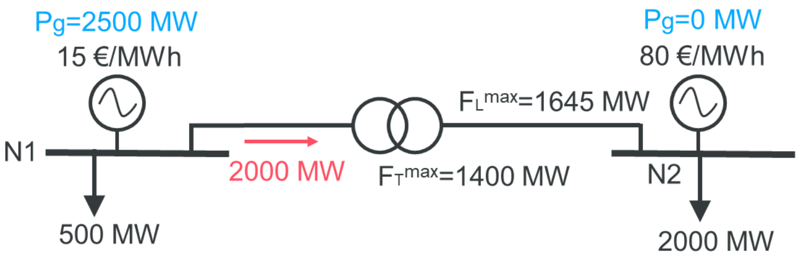

Figure 3-1: Illustrative physical congestion

This discussion can appear to focus on a technical detail, but the chosen way will impact elements that are considered as physically congested, and the way physical congestions must be detected. For instance, the second way will lead to considering as physically congested the grid elements that are not limiting the socio-economic welfare in practice because other grid elements are more constraining but would be limiting the socio-economic welfare in case those other grid elements would have an infinite capacity. It gives thus a comprehensive view on the network, which however risks leading to consider congestions that would never arise in practice, while the first way only shows the dominant congestions (the most constraining elements). For grid planning, it is important to identify all the elements that could potentially limit the most economical transfer of power, as benefits of a grid reinforcement targeting dominant congestions could be hampered by initially hidden congestions. However, in the context of a bidding zone review it does not appear relevant to identify grid elements that are not limiting the socio-economic welfare in practice, as the border of bidding zones should correspond to dominant congestions and not to the hidden congestions with an indirect lower impact on the socio-economic welfare. Consequently, we recommend adopting mainly the first way to define physical congestions, which is consistent with the approach applied in Australia and in the U.S. However, it must also be recognized that avoiding any violation of operational security limits is not always possible, for instance if control means are lacking. This is for example the case in distribution systems where overloads cannot be always avoided in the lower voltage levels. We recommend thus to include as well that reality in the definition to make it robust.

In line with that recommendation, we propose then to slightly adapt the definition of the CACM Regulation in the following way:

> *'physical congestion' means a~~ny~~ network situation on one or several network elements simultaneously where ~~forecasted or realised power flows violate the thermal limits of the elements of the grid and voltage stability or the angle stability limits of the power system~~ a further increase of power flows on this network element(s) would lead to, or increase, the violation of operational security limits;*

Note that the concept of "operational security limits" is already explicitly defined in the CACM Regulation.

[54] Note that the formulation "further marginal increase of that welfare" is important in this context, because a replacement by "full achievement of the maximal welfare" would lead to the same effects as the second interpretation.

3.2.2 Market congestion

We propose to broaden the scope of this definition beyond day-ahead and intra-day market coupling, by slightly modifying it in the following way:

"market congestion" means a situation in which the economic surplus ~~for single day-ahead or intraday coupling~~ during capacity allocation has been limited by cross-zonal capacity or allocation constraints.

It implies that the existing definition of "economic surplus for singe day-ahead or intraday coupling" must then be also slightly revised to remove the explicit reference to only day-ahead and intraday market coupling.

3.2.3 Areal congestion

We propose to adapt the current general definition of congestion in the Electricity Regulation introducing the concept of **areal congestion**, to explicitly deal with the exchanges that determine congestions. In particular, the Article 14 of the Electricity Regulation states that "bidding zones shall not contain such structural congestions", but it is unclear how to consider if a bidding zone contains a congestion as defined in the Electricity Regulation. For this reason, we propose to amend the **congestion** definition to introduce the concept of areal congestion and remove any ambiguity:

"areal congestion" means a situation in which all requests from market participants to trade between two network areas cannot be accommodated simultaneously because they would significantly ~~affect the physical flows on network elements which cannot accommodate those flows~~ contribute to a physical congestion on at least one network element;

As this definition continues to use the existing reference to network area(s), which is currently not explicitly defined in the regulatory framework, we propose to define it as follows:

"network area" means a group of nodes.

This new definition brings two main comments. First, the contribution to a physical congestion must be understood as follows: it entails power flows going in the direction of the congestion. It means that, if an exchange between two network areas tends to alleviate/resolve a congestion, it does not contribute to it. Second, the word "significantly" appears important for large meshed electric power systems such as the European one. Indeed, an exchange between two network areas will impact transmission elements that are far from these two areas, but sometimes very weakly. For instance, an exchange between two areas in Portugal would theoretically impact power flows in Poland, but this impact would be so weak that it can be considered negligible. In order to avoid the identification of a congestion between two areas due to a congested grid element located very remotely from these areas and supporting a negligible share of the exchange between these two areas, a significance threshold is desired. The definition itself does not precise the criterion to consider if there is a significant contribution or not, which is on purpose. A proposition will be formulated in Chapter 4.

3.2.4 Structural congestion

The last definition to clarify is the one for structural congestions. As explained above, an implicit idea of location is currently present behind the concept of structural congestion, without being sufficiently explicit about the way a congestion should be located. In particular, it is unclear if a structural congestion refers to a congested grid element or to a congestion between specific network areas (i.e., to an areal congestion). Since the Electricity Regulation states that bidding zones should not contain structural congestions, it appears more logical to associate structural congestions to areal congestions. Indeed, let's assume that a grid element within a bidding zone A is heavily congested due to loop flows originating from bidding zone B, and that internal flows of bidding zone A marginally impact that grid element. It would be useless to split bidding zone A on both side of that grid element: loop flows originating from bidding zone B would remain at the same level. The solution should be the split of bidding zone B, for example in the two areas whose exchanges are contributing to the physical congestion. Therefore, we need to consider that there is a structural congestion within bidding zone B, corresponding to an areal congestion, and that there is no (or not necessarily a) structural congestion in bidding zone A although there is a physical congestion.

An areal congestion can only be identified if the two areas in question are predefined (e.g., in bidding zone review one needs to predefine alternative bidding zone configurations). Hence, the criteria of unambiguous definition and geographical stability over time mentioned in the definition of structural congestion in the CACM Regulation is straightforward, since such predefined areas would obviously fulfil them. The criterion of predictability of congestion can also be considered as always fulfilled given that a network situation can always be forecasted and modelled. Thereby, if one predefines two network areas and tests them for congestion and structural congestion, the only remaining criterion on whether there is a structural congestion between these two areas is the frequency of occurrence of congestion between these two areas.

Consequently, we propose to slightly amend the definition of structural congestion to emphasize the fact that structural congestions should refer to areal congestions:

> *"structural congestion" means an areal congestion that is capable of being unambiguously defined, is predictable, is geographically stable over time, and is frequently reoccurring under normal electricity system conditions.*

As a concluding comment, we can notice that this definition removes ambiguity to most attributes (unambiguously defined, predictable, geographically stable over time), while keeps a door open for interpretation regarding the word "frequently", which is on purpose. A proposition will be formulated in Chapter 4.

3.3 Interdependences

The proposed set of definitions clarifies one of the key elements of uncertainty in the definitions currently available in the CACM Regulation and Electricity Regulation, namely the relationships between the different types of congestion. Such interdependencies are illustrated in the figure below, which builds a clear and hierarchical view of the different congestion types.

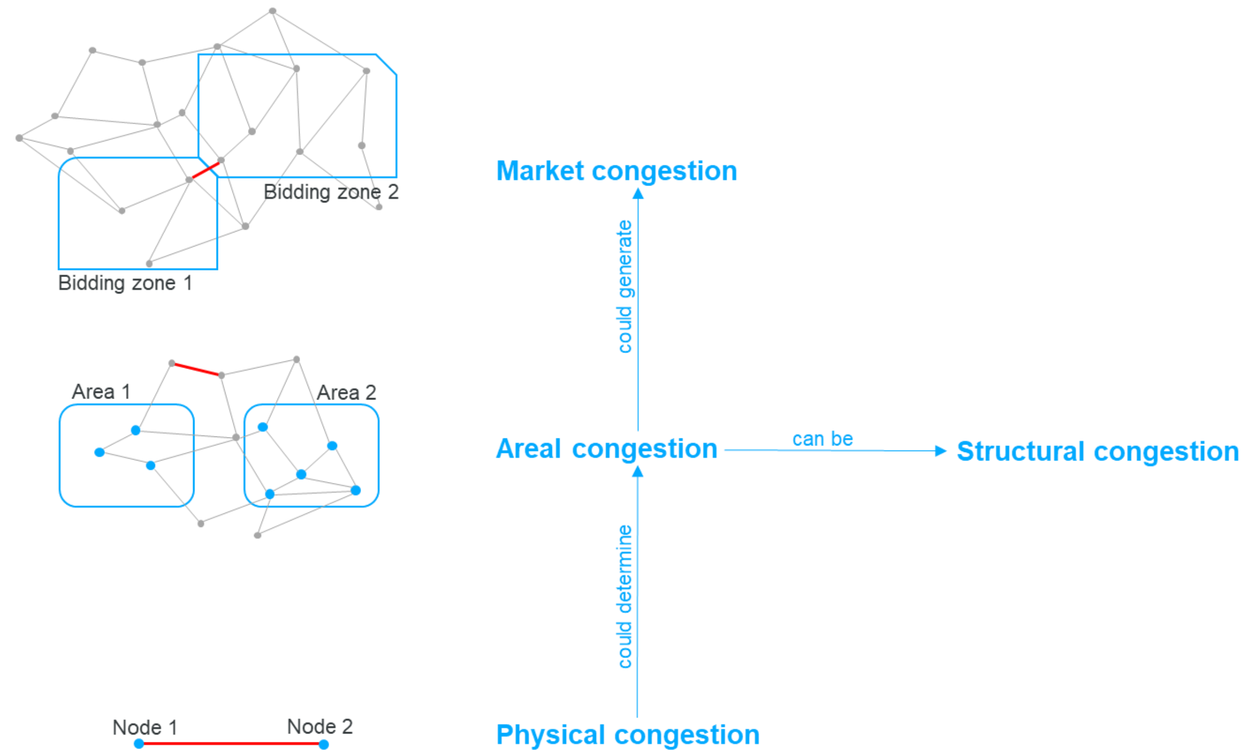

Figure 3-2: Interdependencies between congestion types

Physical congestions happen whenever the power flow(s) on a network element (or a group of network elements) reaches (or potentially exceeds) associated operational security limits. This event represents the first signal of the limitations of the network in fully fulfilling the requests of all the actors. This means that technical limits on congested grid elements are reflected into a limitation in the market exchanges and in the sub-optimal dispatching of resources.

Therefore, the presence of physically congested elements hampers the possibility of market participants to freely trade electricity, if such trade contributes to the physical congestion. Hence, it can be claimed that physical congestions could determine areal congestions, if the contribution of such areal congestion to physical congestions is significant (see Section 4.3 for details on the significance threshold).

Trades between areas often present a recurring pattern, guided by the available generation as well as the requested load at each node. The same areal congestion could be determined by different physical congestions, as it may impact different network elements at different times, based on the overall flow in the system. Hence, different physical congestions may be traced back to the same pattern of exchanges between areas, which then occurs and impacts the network with a certain frequency. If such condition is recurrent and is often limiting the efficiency of electricity trades, then it is crucial to reassess the structure of the market and consider reconfigurations that would better reflect reoccurring patterns in the network. For this reason, it is relevant to observe areal congestions and evaluate their structurality. Namely the concept of structural congestion is currently only used in the context of the bidding zone review (see Article 14(1) of the Electricity Regulation). On the contrary, it is not as meaningful to analyze the structurality of physical congestions because, as mentioned in Section 3.2.4, it would not have any direct consequence or valuable information on the limitations imposed by the market structure.

Finally, depending on the location of the areas involved in the areal congestion and on the congested grid elements affected by such trade, the limitations could escalate to cross-zonal capacity constraints, thus causing market congestion. Therefore, an areal congestion could generate a market congestion, if areas correspond to bidding zones. Also in this case, assessing the structurality of the congestion is not relevant, as a market congestion points directly (in case the flow-based approach is used) or indirectly (in case the coordinated NTC-based approach is used) to specific network elements without providing information on the trades generating the market congestion.

These concepts will be further clarified in the next Chapter, where the identification and characterization of the types of congestions will be discussed and presented on test systems, thus highlighting the steps needed to recognize and analyze the different categories, based on the updated definitions.

4. Identification and characterization of congestion

Chapter 3 proposed improvements to the definitions related to congestions but did not explain how to apply them concretely to identify congestions and left open questions regarding boundaries between structural and non-structural congestions. This Chapter will thus propose detailed methodologies and criteria to identify and to characterize congestions, in particular to distinguish structural and non-structural congestions, and will demonstrate the applicability of these methodologies. However, before developing the methodologies, it must be emphasized that two types of assessments can be conducted: “backward assessments”, in which past (historical) data are used, and “forward assessments”, in which simulation data of future grid conditions are used. This is why this Chapter will start with Section 4.1 elaborating on these two types of assessments. Then, as Chapter 3 explained that structural congestions are linked to areal congestions and that areal congestions can be determined by physical congestions (based on the proposed improved definitions), this Chapter will first propose methodologies to identify and characterize physical congestions (Section 4.2), then a methodology to identify and characterize areal congestions (Section 4.3), and finally a methodology to draw boundaries between structural and non-structural (areal) congestions (Section 4.4).

4.1 Backward and forward assessments

A first way to identify congestions, called “backward assessment”, could rely on past (historical) data, coming mainly from the coordinated capacity calculations, from the market outcomes (capacity allocation), and from coordinated redispatching and countertrading processes. For instance, grid elements actually limiting the optimal socio-economic welfare could be identified based on binding constraints following the market clearing, and/or following the optimization of remedial actions. This first way has the advantage to be based on real data (and thus not on simulation data), reflecting congestions that really impacted the economic operation of the European electric power system. However, it has the inconvenience of reflecting only the past, which means that its relevance for the management of congestions in the future might be limited. For example, the Electricity Regulation requires bidding zone borders to be based on “long-term, structural congestions”. It requires also from the methodology for the bidding zone review to be based on “structural congestions which are not expected to be overcome within the following three years”. To demonstrate that we are facing a structural congestion meeting these criteria, a backward assessment is thus not sufficient, and must be complemented by what we can call a “forward assessment”. Forward assessments must rely on simulation data, such as the ones that can be generated by market simulations or by production cost simulations.

The two approaches are currently used by ENTSO-E to identify congestions: Bidding Zone Technical Reports identify congestions based on historical data (backward assessments), while Bidding Zone Reviews make use of simulation data such as the LMP study (forward assessments). It shows the complementarity between the two approaches. Consequently, they will be both discussed within this report. However, due to the fact that there is almost no publicly available historical data, the applicability of methodologies will be demonstrated only for forward assessment and not for backward assessments.

Regarding backward assessments, it is worth mentioning that the succession of markets (long-term forward markets, day-ahead market, intraday market, balancing market) and the uncertainty associated to the load and to the generation complicate the identification of congestions. For instance, a grid element could appear as congested in the day-ahead market coupling but could finally be used under its thermal capacity in real time because generation from renewable energy resources has significantly deviated compared to the initial forecast. This complexity will have to be considered in the methodology to identify them.

Regarding forward assessments, many simplifications are adopted by software tools used by utilities compared to the actual complexity of electricity markets[55]: (i) a perfect foresight assumption is used (e.g., no forecast error on the load and on the generation), and (ii) in line with the former assumption, the electricity market is simulated in a single step (like a centralized day-ahead market clearing), without considering the successive markets. Examples used to illustrate and to demonstrate the applicability of methodologies will rely on these simplifying assumptions.

[55] Some research-grade software tools might be more advanced but, to the best of our knowledge, they are not yet used by utilities to analyze a power system like the European one.

4.2 Physical congestions

Subsection 3.2.1 explains that there are two different ways to define physical congestions: either based on binding operational security limits which limit the marginal increase of the total socio-economic surplus when network constraints are taken into account, or based on the violation of operational security limits arising from the dispatch of all requests from market participants to trade electricity disregarding network constraints. It proposes then to improve the existing definition mainly with the first way in mind. Consequently, this Section will be strongly based on the first way. However, the second way will be briefly discussed as well, as the first way might not be always fully practicable (e.g., distribution systems). It is worth to emphasize in particular that the two alternative definitions differ in the stage of the market process to which they refer for the detection of physical congestions. In the first way, the mention of socio-economic surplus implies a detection process that starts from the results of the market coupling and of the optimized redispatch process. In the second way, all requests from market participants must be assessed, i.e., an unconstrained market run is needed.

Furthermore, as explained by the previous Section, backward and forward assessments are both needed. Therefore, this Section will first elaborate on forward assessment (Subsection 4.2.1), and then on backward assessment (Subsection 4.2.2).

4.2.1 Forward assessment

Given the definition of physical congestion on a grid element proposed in Subsection 3.2.1, its identification consists in spotting the elements that are limiting the socio-economic surplus due to their operational security constraints. In particular, the methodology presented in this document will focus of the thermal capacity limit. There are multiple ways to perform this task:

- **Security Constrained Optimal Power Flows/Unit Commitments (SC-OPF/UC).** An OPF/UC considering security constraints (i.e., a SC-OPF/UC) will maximize the socio-economic welfare while respecting operational security limits. Binding constraints will correspond naturally to physical congestions. This is the process followed by the ENTSO-E LMP study[56] and is the most straightforward approach. However, it might lead to intractable problems for large systems when unit commitment constraints are considered (unaffordable computation times). Furthermore, such a one-step optimization process neglects the complexities of a zonal market and could lead to too optimistic dispatches (e.g., if constraints inherited from the market clearing during the redispatch process is hampering the implementation of the most optimal dispatch).
- **Zonal market simulations + Redispatching simulations.** To be more realistic and to obtain optimization problems computationally tractable, the zonal market can then be simulated first[57], and operational security limits violated by the outcome of the market are then resolved by redispatching (including countertrading) formulated as a specific SC-OPF/UC (potentially able to consider intertemporal constraints[58]). This is the process followed by the study for Continental Europe in the framework of the second bidding zone review. Physical congestions gather then both binding constraints at the level of the market clearing and after redispatch[59].
- **Unconstrained market runs.** We could also imagine simulating a market[60] without any transmission constraint (i.e., infinite cross zonal capacities), and performing a security assessment to identify if operational security limits are violated. It would identify physical congestions according to the alternative way explained in Subsection 3.2.1, but it could serve as a proxy for the chosen way to determine physical congestions.

In order to illustrate the process of physical congestion identification in the context of a forward assessment, a small network is adopted as an example on which to apply all the different approaches. The network is shown in the figure below and composed by two bidding zones, four buses and four generators. The flows in the network are regulated by the reactance of the lines and are bound by their technical limits. Figure 4-1 shows the starting conditions of a single time step, assuming it replicates for the whole timeframe under consideration (e.g., a full year). For the sake of simplicity, the example does not consider contingencies. Hence, only N condition is analyzed.

[56] ENTSO-E, "Report on the Locational Marginal Pricing Study of the Bidding Zone Review Process," 2022.
[57] Note that all requests to trade must be considered at this stage.
[58] As it is a forward assessment, there is a unique market simulation and then a unique redispatch simulation.
[59] No uncertainty is considered in a forward assessment, so real-time flows correspond to the flows after redispatch.
[60] Idem, all requests to trade must be considered.

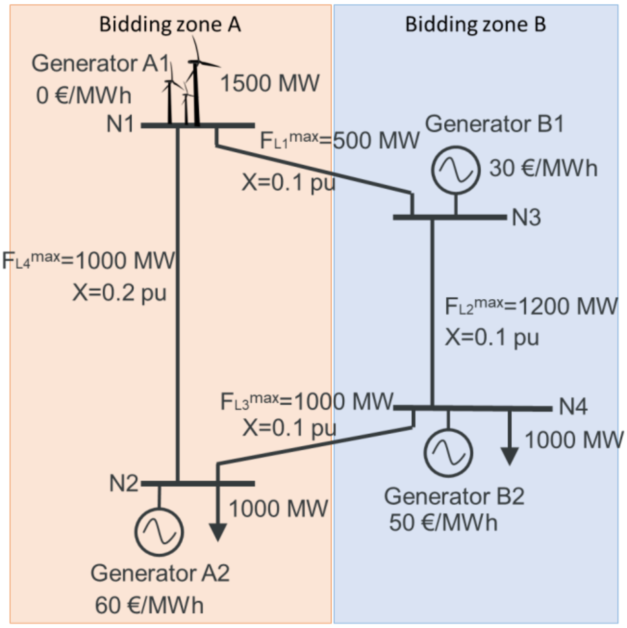

Figure 4-1: Toy model for identification of congestions

4.2.1.1 Security Constrained OPF

Physical congestions can be identified by means of a Security Constrained OPF. This method employs simulation data to perform a single-step market process, analogously to what is carried out in the LMP study that provides the inputs for the Bidding Zone Review process. Therefore, this last approach provides results suitable for forward assessments.

Given the size of the toy model, N-1 constraints are neglected and a simple OPF enforcing that the flows must be below thermal ratings in the N sate (i.e., operational security limits are only considered for the pre-contingency state), , is solved to illustrate the methodology in this section. Flows on L1 and L2 are active constraints, thus highlighting the presence of physical congestions, while lines L3 and L4 have working conditions far from their thermal limits.

Hence, the flows of lines L1 and L4 appear consistent with the market structure of the network, while the condition of lines L2 and L3 question the effectiveness of the current split between bidding zones.

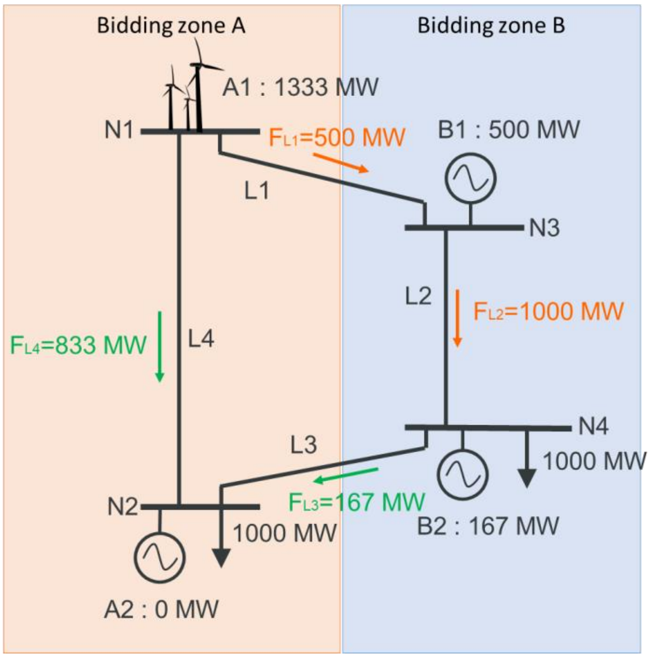

Figure 4-2: Security Constrained OPF solution

The Security Constrained OPF allows the identification of the dominant congestions. Indeed, the active constraints present the most pressing limitations of the market. However, there may be lines characterized by flows below their technical limits that would be overloaded in case of unconstrained market run. This limits visibility on congestions. However, it allows to prioritize and to avoid dealing with congestions that arise in an ideal and unconstrained fashion but are not an issue in the real operation of the system.

4.2.1.2 Zonal market simulation + Redispatching & Countertrading

The second approach to identify congestions is to look at the market process and spot the physical congestions that arise throughout the steps. It is worth pointing out that the market clearing optimization will only include the cross-border lines L1 and L3; hence, internal lines L2 and L4 are not CNEs. Moreover, the market clearing is based on constrained nodal OPF, which does not require the definition of Generation Shift Keys (GSKs).

In particular, after the market clearing, capacity on cross-border lines is allocated and active constraints represent physical congestions according to definition in 3.2.1. These will also represent market congestions, based on the CACM Regulation definition. The results of the market coupling are shown in Figure 4-3, where the cheap generation in node N1 cannot be fully exploited because of the thermal limits on cross-border line L1. Analogously to the previous method, this points out a proper reflection of market signals on bidding zone structure. On the contrary, the underusage of line L3 encourages to evaluate whether to merge nodes into the same bidding zone.

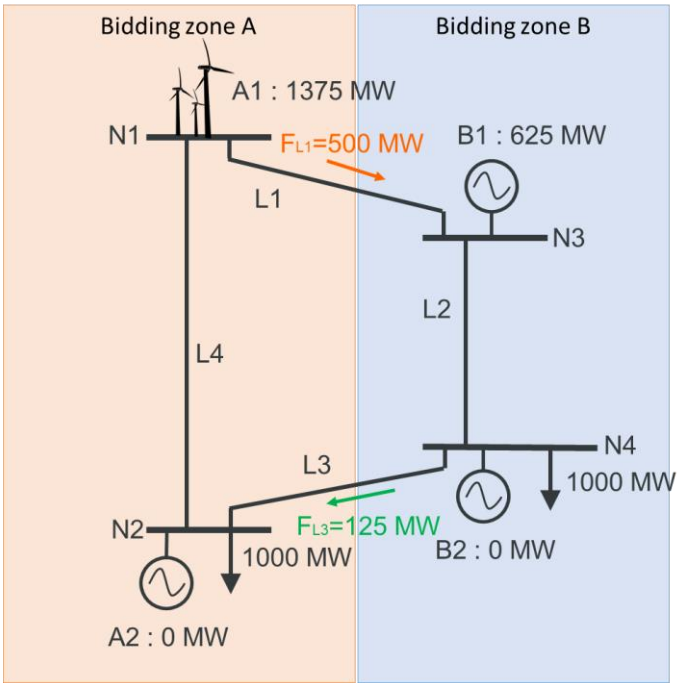

Figure 4-3: Capacity allocation

The dispatch inside the bidding zones reveals an overload on line L2, as shown in Figure 4-4. Hence, the forecasted physical congestion determines the need to redispatch to bring the system within the operational limits in the most effective and economically efficient way, according to Article 20 of the methodology for coordinated redispatching and countertrading[61].

[61] ACER Decision on Core RDCT Methodology: Annex I, "Methodology for coordinated redispatching and countertrading for the Core CCR," 2020.

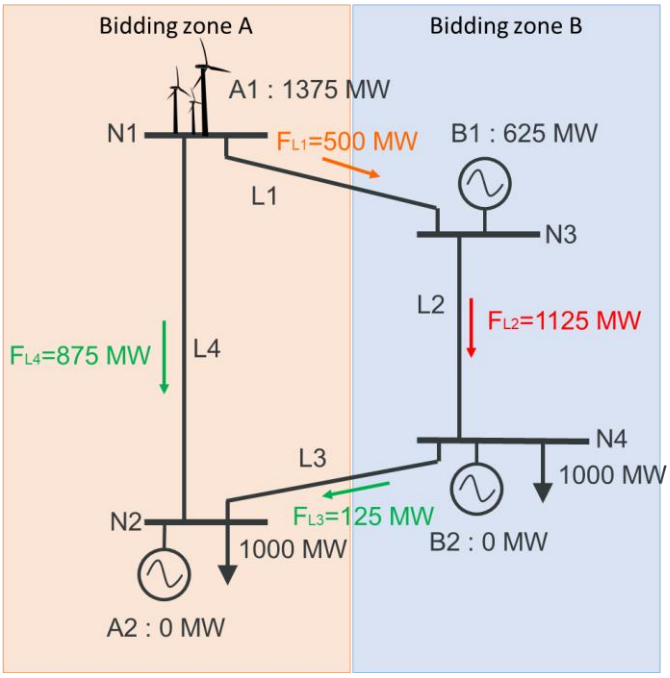

Figure 4-4: Internal power flow computations

Assuming the redispatching happens in accordance with that methodology, i.e., in the most economical way, its outcome produces the same system configuration as the OPF presented in Subsection 4.2.1.1. this is not always the case in complex systems, where there are constraints limiting the degrees of freedom in the redispatching and countertrading phase, possibly leading to suboptimal configurations. In Figure 4-4, the redispatching and countertrading operations lead to a reduction of power injected by generators A1 and B1, compensated by increased generation from generator B2. The flow on line L2 in post-allocation phase is bounded by its technical limits and is not able to accommodate all market requests, thus revealing a physical congestion. Considerations on cross-border lines remain unchanged, while flow in line L4 is well below the limit and thus not affected by congestion issues.

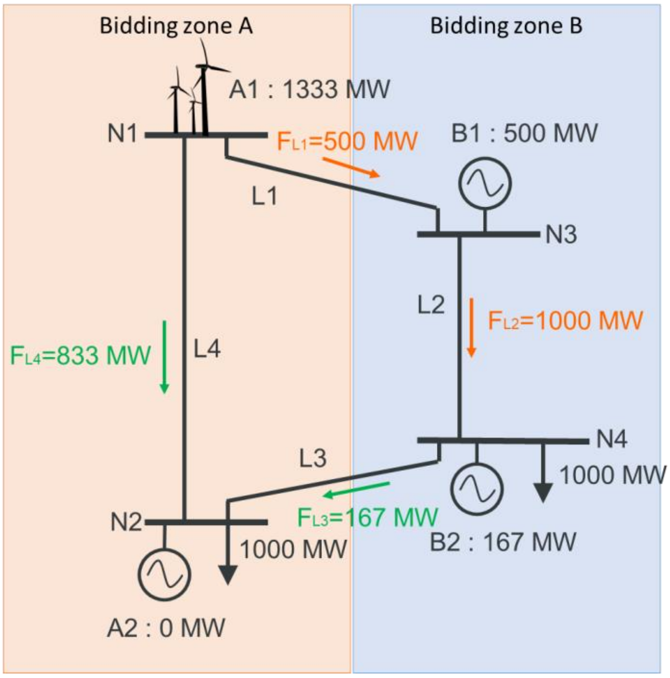

Figure 4-5: Results of redispatching and countertrading

Analogously to the first approach presented in Subsection 4.2.1.1, only dominant congestions can be identified in the form of binding limits, given the presence of cross-border constraints in the capacity allocation phase and line limits in redispatching. Moreover, physical congestions are partially identified after the market coupling (cross-border lines, hence market congestions as well), while the rest of them (internal lines) is spotted after redispatching. In the case of the EU system, the inclusion of CNEs in the market clearing model, allows to widen the identification of physical congestions to more network elements, yet the full visibility is only reached after redispatching.

4.2.1.3 Unconstrained market run

Figure 4-6 shows the least-cost market solution disregarding thermal limits on physical elements. An overload can be spotted on lines L1 and L2.

Congestion on L1 concerns a cross-border line between bidding zones, which suggests that the structure of bidding zones properly reflects the market signals.

On the contrary, congestion on L2, which is internal to the bidding zone, highlights the inability of bidding zone B to accommodate the requests from the market without hitting internal limits. Hence, a reconfiguration of bidding zones is necessary.

Finally, given that the flow in cross-border line L3 is well below its limits, it is worth to further investigate and evaluate the possibility to merge bidding zones. Following a similar line of thought, the absence of congestion on the internal line L4 suggests a proper local configuration, with no need of further attention.

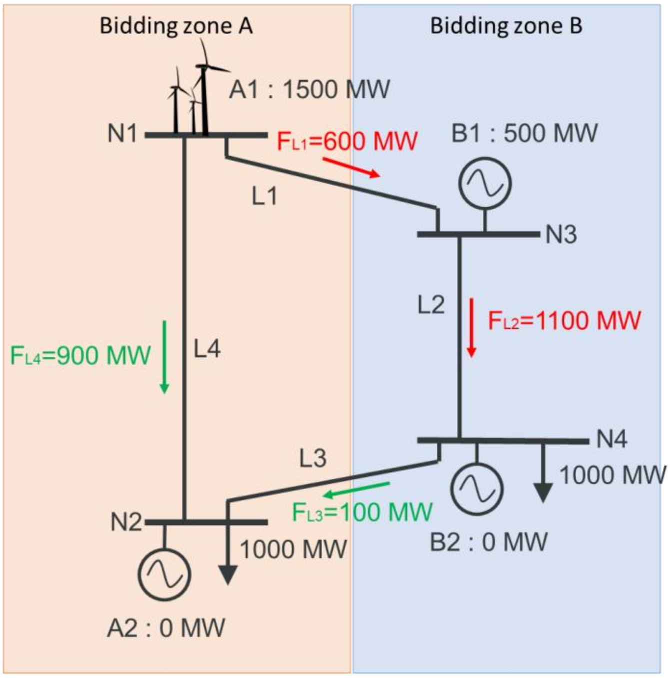

Figure 4-6: Unconstrained market solution

The absence of technical limitations allows to provide a comprehensive view on the optimal economic dispatch and on the related network flows. Therefore, all the network elements breaching their limits can be easily identified. However, they do not necessarily relate to physical congestions as defined in Subsection 3.2.1, as the method does not allow to discriminate between the limits that hinder the maximization of the economic surplus (any marginal increase of the welfare comes with the violation of operational security limits), and the ones that would not represent a limitation in practice, because less stringent than others (the associated violation would not arise because preceded by more constraining elements).

4.2.1.4 Discussion

In the specific context of forward assessment, the unconstrained market runs appear to be the most appealing approach from a computational point of view. Indeed, no grid constraint is included in the optimization problem. However, it is likely to over-identify physical congestions, as some violations would arise when all requests from market participants are accommodated to reach the maximum welfare (disregarding transmission constraints), while they would not emerge and not be relevant when such constraints are considered, as in SC-OPF. An example of overestimation is provided in Section 3.2.1.

The SC-OPF/UC approach is the most complex one from a computational point of view. In particular, it might lead to intractable optimization problems if not tackled by efficient numerical techniques (e.g., decomposition methods). It has nevertheless the advantage of staying conceptually simple (i.e., straightforward formulation of the optimization problem). The zonal simulations coupled to redispatching simulations might thus provide a good trade-off from a computational point of view[62]. However, no consensus currently exists for the associated mathematical formulation (e.g., on the way unit commitment decisions can be changed during the redispatch process). It requires thus first to define a unique approach.

4.2.2 Backward assessment

Methodologies for forward assessments could make simplifying assumptions on the organization of the electricity market, and all required data can be generated by simulation. This is completely different for backward assessments: methodologies must consider the way the electricity market is organized and the associated intrinsic availability of data[63]. Two major specificities must be considered.

First, the European electricity market is not currently based on a pool (centralized) trading, but on bilateral trading combined with power exchanges. It implies that the use of power exchanges is optional for participants: generators are not obliged to sell their entire production to a pool and suppliers are not obliged to purchase their entire demand from a pool. Consequently, the unconstrained market runs would require collecting from each generating company the way they would have dispatched their generation between the different generators in case the market would have not consider transmission constraints, which seems to be hardly applicable. Similarly, the SC-OPF/UC would require collecting individual bids for each generating unit, which does not appear realistic[64]. It implies that only the identification of congestions based on the outcomes of the market clearing and to the outcome of the redispatch process appears applicable. This approach has also the merit of being based on already existing processes, which means that it has the advantage of exploiting easily available data retrieved throughout the market steps.

Second, there is no unique market clearing, but a succession of them. We can mention long-term forward markets (e.g., annual and monthly), short-term forward markets called sometimes also spot markets (day-ahead and intraday) and the balancing market.

Third, the violation of operational security limit in real time cannot be always avoided, due to limited control means and/or imperfect forecasts.

Therefore, we propose to consider that a grid element or a group of grid elements should be considered as the cause of a physical congestion for a specific market time unit if the related constraints are binding for at least one of the market steps, or at the level of the redispatch process, or if the related constraints are violated in real time.

4.3 Areal congestions

Physically congested elements represent the signal of a system that is unable to fully accommodate market request for trade, ending up in a sub-optimal utilization of resources. Moreover, physical congestions represent a cost for the system as well as a technical issue to be solved in the short term/real time. Hence, the presence of physically congested elements informs on where to strengthen the network.

However, the information provided by **physical congestions** is **not sufficient to trace the root causes of the market limitations and formulate long term solutions** in the zonal market (e.g., bidding zone review).

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[62] Although the feedback from the second bidding zone review indicates that it remains challenging when the optimization of remedial actions is included in the process.
[63] Note that methodologies should not be bounded by the data currently available, as additional computations might be performed, but by what can be realistically available
[64] We can note for instance that, in the initial proposal of European TSOs for "Generation and Load Data Provision Methodology", the door was opened to request from power generating facility owners an indicative estimate of marginal cost, but it was removed from the final submission following a strong opposition from stakeholders.

This is instead the case for areal congestions (as defined in Section 3.2.3) that look at the exchanges between areas (i.e., groups of nodes) and their impact on physically congested elements

The figure below illustrates the steps needed to identify an areal congestion. First of all, the areas to be evaluated need to be identified. Given that the purpose of the evaluation is to trace the root causes of physical congestions, the **exchanges under analysis must refer to trades of electricity**. In other words, the first area must have at least one generator and the second area must have at least one load.

In a complex system, multiple generators and loads populate the network affecting flows on lines, thus associating line flows to a specific trade is not straightforward, yet pivotal: the selected exchange may contribute to a congestion, but it could as well relieve it. Hence, **assessing the direction of the exchange-related flow in physically congested elements is the key to identify areal congestions**. In order to retrieve this information, it is necessary to assess the net positions of the two selected areas, so that the exporting and importing area can be identified. Then, the use of Generation and Load Shift Keys (GLSKs) and power flow computations allow to identify flows and their directions.

At this stage, if the exchange determines a flow in the physically congested elements that is in the opposite direction with respect to overall flow in the lines, then we can directly conclude that there is no areal congestion. If instead the directions match for at least one physical congestion, then the exchange actively participates to the formation of that physical congestion.

Still, the impact might not be relevant, meaning that the causes of congestion should be sought elsewhere. For this reason, a significance threshold is set, in order to flag as areal congestions only the exchanges that give a decisive contribution in overloading the network element and which, consequently, are those on which it is most effective to act to solve the issue. The indicator adopted to verify this condition is the area-to-area PTDF, whose absolute value provides information on the impact of the exchange between areas on the flow on a specific network element. The **significance threshold for area-to-area PTDFs is set to 5%** in accordance with Article 5 of the Core capacity calculation methodology[65]. The significance threshold therein is defined based on Article 29(3)(b) of the CACM Regulation, which requires ignoring in capacity calculation those critical network elements that are not significantly influenced by the changes in bidding zone net positions (which correspond to cross-zonal exchanges). The threshold of 5% could be subject to review in future (e.g., Article of Core capacity calculation methodology also requires an analysis of raising this threshold up to 10%). However, it makes sense that the significance threshold for areal congestion and significance threshold for cross-zonal exchange remain the same as they essentially describe the same impact, i.e. whether cross-zonal (areal) exchange has a significant impact on a network element.

[65] ACER Decision on Core CCM; Annex I, "Day-ahead capacity calculation methodology of the Core capacity calculation region," 2019.

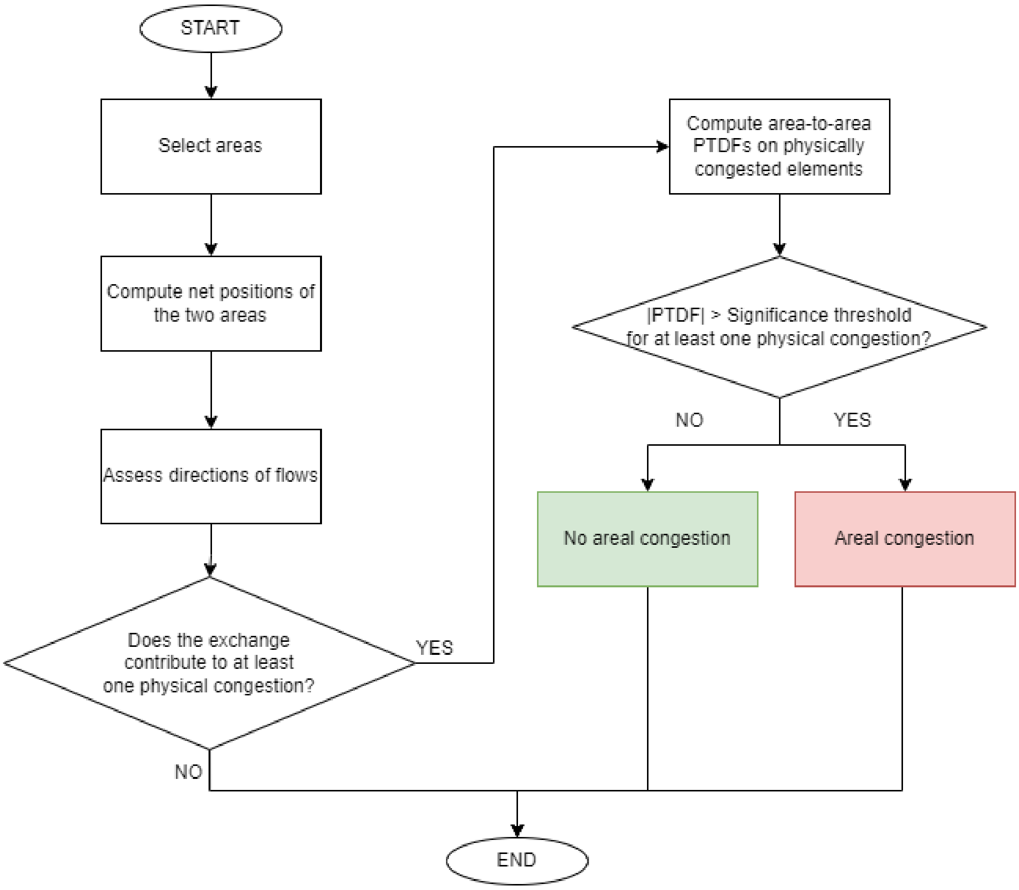

Figure 4-7: Identification of areal congestions

4.3.1 Congestion identification on a toy model

In the example of the toy model, assuming the market coupling leads to the system configuration discussed in 4.2 and shown here below, areal congestions between areas made up of individual nodes are analyzed. This very simple system is here adopted as the identification of areal congestion can be carried out simply by inspection of the system. In this way, the definition of areal congestion provided in Section 3.2.3 can be tested, to be then scaled up to bigger networks.

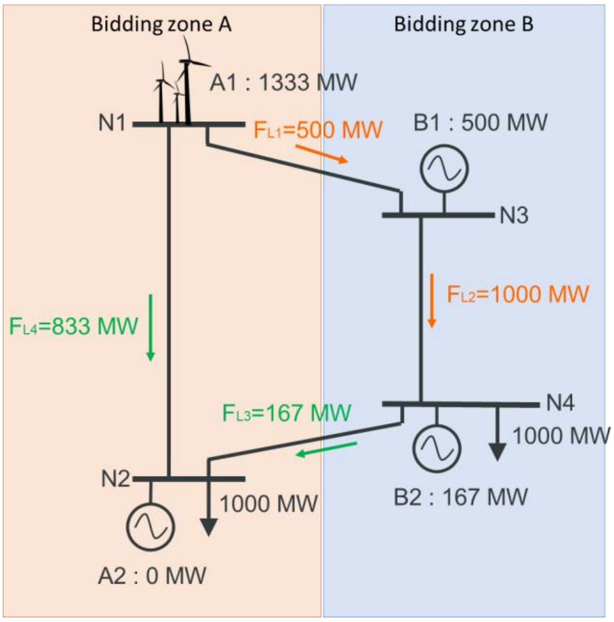

Figure 4-8: Market outcome

All the pairs of nodes are evaluated in the table below:

Pair of nodes	PTDFs	Areal congestion assessment
N1&N2	$\lvert PTDF_{L1}\rvert = 40\%$ $\lvert PTDF_{L2}\rvert = 40\%$	Exchange leads to flows consistent with overall direction in both lines L1 and L2. PTDF above significance threshold. **Areal congestion identified.**
N1&N4	$\lvert PTDF_{L1}\rvert = 60\%$ $\lvert PTDF_{L2}\rvert = 60\%$	Exchange leads to flows consistent with overall direction in both lines L1 and L2. PTDF above significance threshold. **Areal congestion identified.**
N2&N3	$\lvert PTDF_{L1}\rvert = 40\%$ $\lvert PTDF_{L2}\rvert = 60\%$	Exchange leads to flows consistent with overall direction in line L2, opposite direction with respect to L1. PTDF above significance threshold. **Areal congestion identified.**
N3&N4	$\lvert PTDF_{L1}\rvert = 20\%$ $\lvert PTDF_{L2}\rvert = 80\%$	Exchange leads to flows consistent with overall direction in line L2, opposite direction with respect to L1. PTDF above significance threshold. **Areal congestion identified.**
N2&N4	$\lvert PTDF_{L1}\rvert = 20\%$ $\lvert PTDF_{L2}\rvert = 20\%$	No generation in N2, marginal generation in N4, thus we consider transfer of power from N4 to N2. Exchange leads to flows opposite to overall direction in both lines L1 and L2. **No areal congestion identified.**
N1&N3	Not relevant to assess areal congestions, as the two nodes only present generations, hence no trade of electricity is in place.[66]	

Table 4-1: Areal congestions in toy model

In this simple case, the impact of any exchange on single lines is above the significance threshold. Moreover, direction of total flows is determined by only few generators and loads and is therefore strongly reflected in the exchanges under analysis. Indeed, almost all exchanges contribute to at least one line flow in the direction of a physical congestion, hence they are considered as creators of areal congestions. This is not necessarily the case in a complex meshed network, where some exchanges have a very limited influence on congested lines and the presence of numerous generators and loads from the same area causes a partial compensation between flows. Thus, deeper investigation is necessary in order to identify areal congestions in complex systems.

Hence, the scale up of the line of thinking presented in Table 4-1 requires a structured methodology for the decomposition of flows and a further step to identify their direction.

The first task is here performed by computing the net positions of the two areas (according to the Common Grid Model) and distributing the generation of the exporting area using GSKs. Such step is relevant if an exporting and an importing area can be identified, i.e., if one net position is positive and the other is negative. If this is not the case, the analysis does not go further for that specific timestep, as trade between the two identified areas cannot be defined.

Once the flows are decomposed, their directions can be easily assessed by means of a DC power flow. This allows to verify whether the exchanges under analysis contribute to physical congestions. If so, PTDFs are computed and if above significance threshold, areal congestions are identified.

4.3.2 Congestion identification on the European power system

In order to apply the methodology described in the previous subsection, a grid model such as the one published by ENTSO-E in the framework of the bidding zone review is needed, as well as a rule to define GLSKs for each area. However, because the PTDFs depend on the specific grid topology, and because the grid topology might change from one MTU to another, information regarding the topology is also needed.

[66] Note that this case can appear for nodes but should not appear in practice for areas (see next section), as we expect to have always both generation and load in each area.

4.4 Structural congestions

The final bit of the analysis consists in analyzing the outcomes of the identification of areal congestions in order to identify if an areal congestion is structural or not.

As discussed in Subsection 3.2.4, given the above assumption that areal congestion can only be identified if the two areas in question are predefined (e.g. in bidding zone review one needs to predefine alternative bidding zone configurations), the criteria of unambiguous definition and geographical stability over time is straightforward, since such predefined areas would fulfil the criteria of unambiguous definition and geographical stability over time. The criteria of predictability of congestion can also be considered as always fulfilled given that a network situation can always be forecasted and modelled.

Thereby, if one predefines two network areas and tests them for congestion and structural congestion, the only remaining criterion on whether there is a structural congestion between these two areas is the frequency of occurrence of congestion between these two areas. This means assessing the frequency of the areal congestion and verify if above the predefined frequency threshold. However, the definition of such threshold is the most challenging task in the attempt of reducing the ambiguity of the structural congestion definition of the Electricity Regulation. There is no straightforward way to define such a threshold as it depends on perceptions of what the term “frequently” actually means in the context of electricity network congestions. To address this dilemma, the Consultant (with the help of ACER) decided to ask the relevant experts in congestion management on a proper threshold value that would capture the intention of the term “frequently occurring under normal power system conditions”.

The responses provided by the experts highlighted the complexity of the topic and 7 stakeholders proposed suitable threshold (between 1 and 20%), with most responses being in the interval 5÷10% (details about the outcome of the survey are provided in Appendix 7.2). As it is difficult to derive a very exact value, we provide a recommendation based on a range between 5 and 10% and the exact value can be derived subject to legislative discussions and procedure. Hence, this range is here proposed as reference for the assessment of structural congestions.

4.5 From nodes to group of nodes

The same type of analysis (identification of physical, areal and structural congestions) can be scaled up to more complex systems, where it is interesting to consider exchanges between group of nodes (instead of single nodes), as per definition of area in Section 3.2.3. The methodology is then tested on a more complex system, namely a revisited version of the IEEE Reliability Test System (RTS). As show below, it presents 3 bidding zones, 73 nodes and 125 branches. The time frame under analysis is one year.

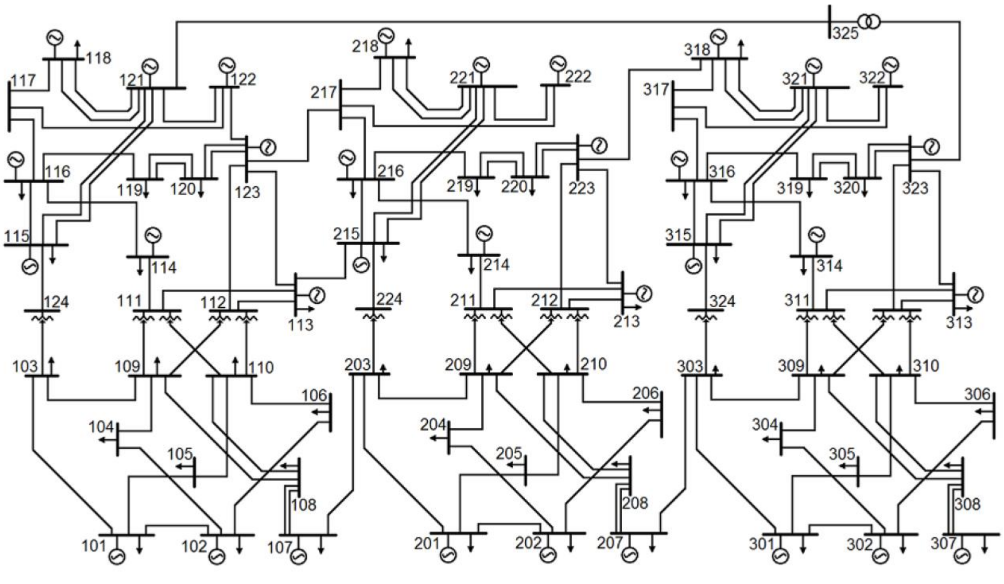

Figure 4-9: Revisited IEEE RTS test system

The methodology applied follows the steps illustrated on the toy model in Sections 4.2, 4.3 and 4.4. In particular, the presence of physical congestions has been identified from the outcomes of a security constrained OPF in N-1 condition (see Section 4.2.1.1); then, areal congestions have been spotted after balancing out the net positions of the two identified areas; finally, a frequency of 10% is considered as threshold for defining structural congestions.

The first pivotal step resides in the selection of the areas. This system represented the case study for a previous work developed by the Consultant on congestion cost allocation in the context of the European project called ASSET[67]. The report highlighted the highest number of congested elements in bidding zone 3. Therefore, this zone will represent the focus of the following tests. In particular, generation in the North of the zone would often exceed the needs of surrounding nodes, while the opposite stands in the South, where loads request power that cannot be fully supplied by the generators close by. This is expected to generate not only exchanges with the neighbouring bidding zone, but possibly internal congestions. Hence, it is relevant to assess the presence of structural congestions inside bidding zone 3.

As physically congested elements are distributed all across the zone, it is not straightforward to recognize the root causes of the issue. Indeed, it is interesting to analyze various set of areas for which the presence of structural congestion is uncertain. For this reason, the impact of trades between nodes listed in the table below are analyzed. Both neighboring and non-neighboring zones are considered, in order to provide a varied set of situations.

Test case	Nodes area 1	Nodes area 2
1	315, 316	323
2	313	314
3	301, 302, 307	318, 321, 322

Table 4-2: Selected nodes for congestion identification

None of the first two test cases leads to a structural congestion, while the third test case highlights the presence of a structural congestion. This confirms the importance of applying the proposed methodology for the identification of structural congestions, as complex systems require dedicated analyses to be correctly interpreted. In all the three cases, the trades between the two sets of areas contribute to physical congestions, which determine the presence of an areal congestion. However, in some cases the relevance of such contribution is below the significance threshold, while in some others the contribution is considered significant but not frequent enough to determine the presence of a structural congestion. The procedure run of test case 3 reveals instead the presence of structural congestions under the following contingencies:

a) Line 303-324
b) Line 305-310
c) Line 308-309
d) Line 308-310
e) Line 313-323
f) Line 315-321
g) Line 315-321
h) Line 315-324
i) Line 316-319
j) Line 323-325
k) Line 325-121

The last line listed connects bidding zone 3 with bidding zone 1, hence the presence of a structural congestion is consistent with the market structure. On the contrary, all the other elements are internal to the bidding zone. This poses a question on the correct configuration of the system and on the possibility to further split it into additional bidding zones.

The analysis confirms the importance of setting a significance threshold on the area-to-area PTDFs in order to correctly assess the presence of areal congestions and prevent widening too much the scope by including trades that are not relevant in practice. In fact, there are cases where it could be said that the trade between

[67] T. Martinelle and P. Henneaux, "Congestion cost allocation in the framework of Art. 16(13) of the electricity regulation," 2021.

the two areas reinforces physical congestion on a network element, but its impact is insignificant and thus negligible. This is the case here, for example, where the exchange between the two selected areas causes a flow on physically congested Line 208-209 (under contingency of Line 323-325 and Line 325-121) in the same direction of the physical congestion. However, the area-to-area PTDF on such line is only 4%, highlighting that the trade between those two areas is structural but does not provide significant contribution to all physical congestions in the network. Indeed, it provides only a negligible contribution to the physical congestion on Line 208-209.

5. Legal/regulatory changes

The previous chapters provided a review of the existing definitions, a proposed set of definitions and means to identify and characterize the new set of definitions. Based on these results, the current chapter 5 propose advice on legal/regulatory changes to the Electricity Regulation and the CACM Regulation in order to accommodate the new set of definitions.

We propose to amend the **Electricity Regulation** by introducing to its Article 2 the definitions of "**areal congestion**", and "**physical congestion**", and by modifying the definition of "**structural congestion**".

We propose to amend the **CACM Regulation** by (i) modifying slightly the definitions of its Article 2 on "**market congestion**", "**physical congestion**", "**structural congestion**", and introducing the definitions of "**areal congestion**", "**network area**", and by (ii) introducing a new article explaining how to identify **physical and areal congestion**.

5.1 Electricity Regulation

PROPOSAL FOR AMENDMENTS TO THE REGULATION (EU) 2019/943 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 5 JUNE 2019 ON THE INTERNAL MARKET FOR ELECTRICITY

I. JUSTIFICATION

The definition of "congestion" and "structural congestion" contained in the Electricity Regulation present certain limitations that hinder the identification of congestion in formal processes such as the EU electricity bidding zone review and reporting on structural congestion. The lack of clarity in this definition and its relationship and applicability in relation to "structural congestion", "market congestion" and "physical congestion" as defined in Article 2 of Regulation 2015/1222 require to be addressed. To face these shortcomings and to align the definitions of "congestion" and "structural congestion" with the foreseen modification of the various types of congestions contained in Article 2 of EU Regulation 2015/1222, the present amendment introduces to the Electricity Directive the concept of "areal congestion", "physical congestion" and sets forth minor enhancements to the definition of "structural congestion".

The current definitions of the various type of congestions do not explicitly address exchanges that determine congestions and do not provide indications on how to consider if a bidding zone contains a congestion. A new concept of "**areal congestion**" is thus defined in Article 2 to explicitly address exchanges that contribute to congestions between network areas. As the definition of areal congestion also directly refer to "**physical congestion**", the definition of physical congestion as foreseen in the proposed modifications of Regulation 2015/1222 is introduced to the Electricity Regulation.

The current definition of "**structural congestion"** lacks explicit clarity regarding its location, whether it pertains to a congested grid element or congestion between specific network areas. To align with Article 14 of the EU Regulation 2019/943, which states that bidding zones must not contain structural congestions, structural congestions should be associated with the introduced concept of areal congestion. The proposed amendment to the definition thus recognizes that structural congestions should be considered as areal congestions, rather than grid element congestions.

I) AMENDMENTS

"Article 2 Definitions

The following definitions apply: [...]

(4) 'congestion' means a situation in which all requests from market participants to trade between network areas cannot be accommodated because they would significantly affect the physical flows on network elements which cannot accommodate those flows;

(5) 'new interconnector' means an interconnector not completed by 4 August 2003;

(6) "physical congestion" means a network situation on one or several grid elements simultaneously where a further increase of power flows on this network element(s) would lead to, or increase, the violation of operational security limits.

(7) "areal congestion" means a situation in which all requests to exchange electricity between two network areas cannot be accommodated simultaneously because they would significantly contribute to a physical congestion on at least one network element.

(~~7~~8) 'structural congestion' means ~~congestion in the transmission system that is capable of being~~ an areal congestion that is capable of being unambiguously defined, is predictable, is geographically stable over time, and ~~frequently reoccurs~~ Is frequently reoccurring under normal electricity system~~e~~ conditions.~~"~~

5.2 CACM Regulation

PROPOSAL FOR AMENDMENTS TO THE COMMISSION REGULATION (EU) 2015/1222 OF 24 JULY 2015 ESTABLISHING A GUIDELINE ON CAPACITY ALLOCATION AND CONGESTION MANAGEMENT

II) JUSTIFICATION

The definitions of "structural congestion", "physical congestion" and "market congestion" constrained in the CACM Regulation present certain limitations that hinder the identification of the various types of congestion in formal processes such as the EU electricity bidding zone review and reporting on structural congestions. The lack of clarity in these definitions and their relationship and applicability in relation to "congestion" as defined in Article 2 of Regulation 2019/943 require to be addressed. To face these shortcomings, the present amendment sets forth minor enhancements to said definitions and introduces the new concept of "areal congestion".

The new set of definitions aims at illustrating the interdependencies between "physical congestion", "areal congestion", "market congestion" and "structural congestion". "Physical congestions" occur when there are bottlenecks in the grid, leading to limitations in market exchanges and sub-optimal resource dispatching. "Physical congestions" determine "areal congestions" when the presence of congested elements hampers the possibility of market participants to freely trade electricity, given that such trade contributes to physical congestion. Different physical congestions can lead to the same areal congestion, impacting various network elements at different times based on overall system flow. "Areal congestions" can either give rise to "market congestion" or "structural congestion". On the one hand, depending on the location of areas involved in an "areal congestion" and the congested grid elements affected by trade, limitations of the network can escalate to cross-zonal capacity constraints, leading to "market congestion". On the other hand, "structural congestion" can occur when the recurring pattern of trades between areas, influenced by available generation and requested load at each node, leads to the same areal congestion being determined by different physical congestions. These different physical congestions may impact various network elements at different times based on the overall system flow. If this situation is recurrent and frequently hampers the efficiency of electricity trades, it becomes essential to reassess the market structure and consider reconfigurations that better reflect these recurring patterns in the network.

Currently, the definitions of the various type of congestions do not explicitly address exchanges that determine congestions and do not provide indications on how to consider if a bidding zone contains a congestion. The new concept of “**areal congestion**” thus defined in Article 2 explicitly address exchanges that contribute to congestions between network areas. An areal congestion is defined as a situation where all requests to exchange electricity between two areas cannot be accommodated simultaneously and would significantly contribute to a physical congestion. As the definition introduces a new concept of “network areas”, the definition of “network area” as a group of nodes is introduced to the regulation. In order to avoid the identification of a congestion between two areas due to a congested grid element located very remotely from these areas and supporting a negligible share of the exchange between these two areas, a significance threshold is introduced in a new Article 34. This new article gives indication on how to identify areal congestion by analyzing the direction of exchange-related flows in physically congested elements and by applying the significance threshold.

The current definition of “**market congestion**” is limited to day-ahead and intra-day market coupling. The improved definition link “market congestion” to its interdependence with “areal congestion” as, depending on the location of areas and congested grid elements affected, areal congestions can escalate to cross-zonal capacity constraints, resulting in market congestion.

The current definition of “**structural congestion”** lacks explicit clarity regarding its location, whether it pertains to a congested grid element or congestion between specific network areas. To align with Article 14 of the EU Regulation 2019/943, which states that bidding zones must not contain structural congestions, structural congestions should be associated with the introduced concept of areal congestion. The proposed amendment to the definition recognizes that structural congestions should be considered as areal congestions, rather than grid element congestions.

The current definition of “**physical congestion”** is based on the violation of operational security limits due to forecasted or realized power flows. However, there is ambiguity surrounding the concept of forecasted power flows. The amendment proposes a new definition that considers physical congestion as a situation in which one or several grid elements are limiting the total socio-economic welfare (or economic surplus) as a further marginal increase of that welfare would lead to the violation of associated operational security limits, considering contingencies. This revised definition provides a more comprehensive and clear understanding of physical congestion, focusing on its impact on overall economic well-being and operational security. The new definition takes into account the final dispatch resulting from both market coupling and the redispatch process.

I. AMENDMENTS

“Article 2
Definitions
17. ‘areal congestion’ means a situation in which all requests to exchange electricity between two network areas cannot be accommodated simultaneously because they would significantly contribute to a physical congestion on at least one network element.
18. ‘network area’ means a group of nodes.
1~~7~~9. ‘market congestion’ means a situation in which the economic surplus ~~for single day-ahead or intraday coupling~~ during capacity allocation has been limited by cross-zonal capacity or allocation constraints;
~~18~~20. ‘physical congestion’ means ~~any~~ a network situation ~~where forecasted or 35ealized power flows violate the thermal limits of the elements of the grid and voltage stability or the angle stability limits of the power system;~~ on one or several grid elements simultaneously where a further increase of power flows on this network element(s) would lead to, or increase, the violation of operational security limits.
21. ‘structural congestion’ means ~~congestion in the transmission system~~ an areal congestion that can be unambiguously defined, is predictable, is geographically stable over time and is frequently reoccurring under normal power system conditions;

[…]

Article 34 – Identification of physical and areal congestion

l) Identification of areal congestion shall consist of the following steps:
a) Identification of two network areas area between which areal congestion is being tested;
b) Identification of requested exchange between two areas;
c) Identification of physical congestions;
d) Identification of impact of requested exchange on physical congestions; and
e) Identification of significance of the impact of requested exchange on physical congestions.
f) Each of the two network areas being tested for areal congestion shall consist of at least one node, where exporting area shall have at least one generation node and importing area shall have at least one demand node.
g) The requested exchange between two areas shall be identified based on the specific market time unit for which the areal congestion is being tested. In case of backward assessment, the exchange shall be identified based on historical common grid models with underlying historical generation, load and network configuration. In case of forward assessment these shall be identified based on future common grid models with underlying forecast for generation, load and network configuration. The direction of the requested exchange shall be from area with higher net position to area with lower net position.
h) Areal congestion test requires identification of physical congestions. For backward assessment these shall be identified based on the outcome of the day-ahead market coupling, of the intraday market coupling, of the balancing market coupling, of the coordinated redispatch process and on the real time. For forward assessment these shall be identified based on the binding constraints in the market simulation and in the redispatch simulation.
i) The impact of requested exchange on physical congestion shall be assessed by analyzing the power transfer distribution factors for the given requested exchange on the given network elements which are physically congested.
j) The requested exchange has a significant impact on physical congestion on a given network element if the PTDF on such element calculated pursuant to paragraph 5 is equal or higher than +5% (and in the direction of the congestion). If the impact is lower than 5% (or opposed to the direction of the congestion), then the requested exchange has insignificant impact on physical congestion on such network element.
k) Areal congestion between two given network areas for a given market time unit exists when the requested exchange between these two areas has significant impact on at least one physically congested network element.

Alternatively, instead of putting these details into the CACM Regulation, the latter could only provide for a process by which these details would be clarified through dedicated methodology. The following paragraph could thus be added to Article 34 of the CACM Regulation, whereas the provisions above could be used as a basis for developing the methodology.

By no later than [X] months after entry into force of this Regulation, all TSOs shall develop a proposal for a Methodology for clarification of definitions of congestions. The methodology shall clarify practical steps to identify physical congestion, areal congestion, market congestion and whether areal congestion is structural or not. The methodology shall also distinguish how these congestions are identified for congestions occurred in the past as well as congestions expected in the future. The methodology shall also define the data required for such an assessment and identification.

6. Conclusions and perspectives

The regulatory and legal framework around the EU power system has numerous implications on the technical and economic performances of the sector. An important aspect of this framework relates to congestions. Different types of congestions are defined by the CACM Regulation and by the Electricity Regulation. This report showed however that the existing definitions are not fully adequate, as links between them are unclear and elements of the definitions are ambiguous. For that reason, this report proposed improved versions of these definitions. It then demonstrated the applicability of these improved definitions and provided a way to define a clear boundary between structural and non-structural congestions. Finally, it advised on amendments to the CACM Regulation and to the Electricity Regulation needed to implement these improvements. Nevertheless, several degrees of freedom on the way to apply these methodologies remain open on purpose in these definitions. Therefore, they must be complemented by implementation guidelines.

7. Appendix

7.1 Application of existing definitions on a toy model

In order to illustrate the concepts discussed in 2.1.2, a small network is adopted to show our interpretation of definitions of congestions with a practical example.

The network is shown in the figure below and composed by two bidding zones, four buses and four generators. The flows in the network are regulated by the reactance of the lines and are bound by their technical limits.

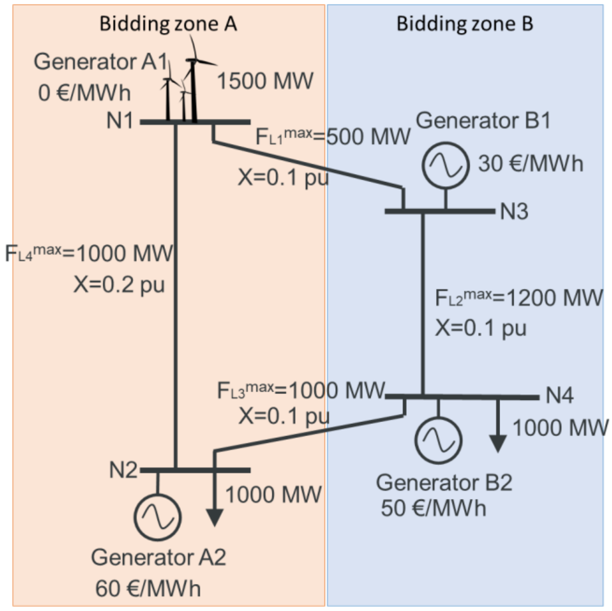

Figure 7-1: Toy model

The unconstrained least-cost option (shown in Figure 7-2) would cause overloading on lines L1 and L2. As L1 is a cross-border line, its thermal limit will be directly considered in the market coupling algorithm; hence, overloading of L1 cannot happen in practice. This does not stand for line L2, as it is internal to Bidding zone B, hence its flow is only evaluated after the capacity allocation process.

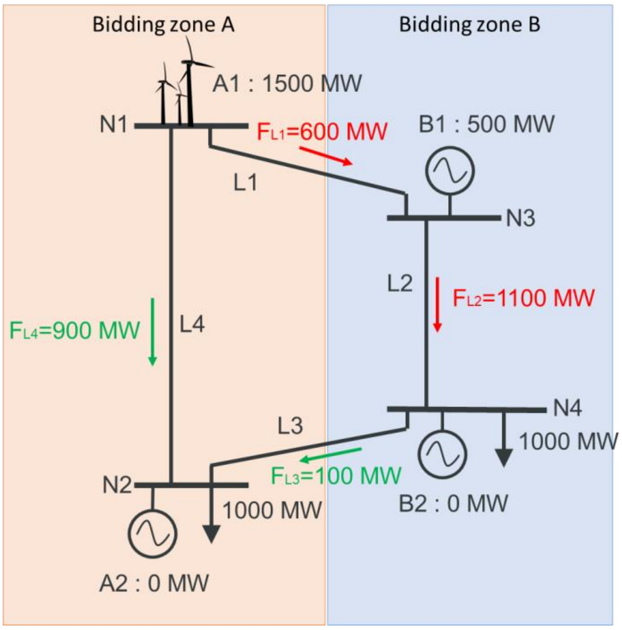

Figure 7-2: Unconstrained least-cost solution

The figure below shows the solution of the zonal market clearing, which embeds the technical limits on lines across bidding zones (lines L1 and L3). Wind production needs to be reduced and be compensated by a more expensive generator, namely B1.

As the thermal limit of L1 is limiting the socio-economic welfare at the level of the market, it is a **market congestion**, directly tackled in the market coupling algorithm. An OPF would lead to the same solution, with the thermal limit of L1 as binding constraint. Therefore, this can be classified as well as a **congestion**, according to the definition of the Electricity Regulation.

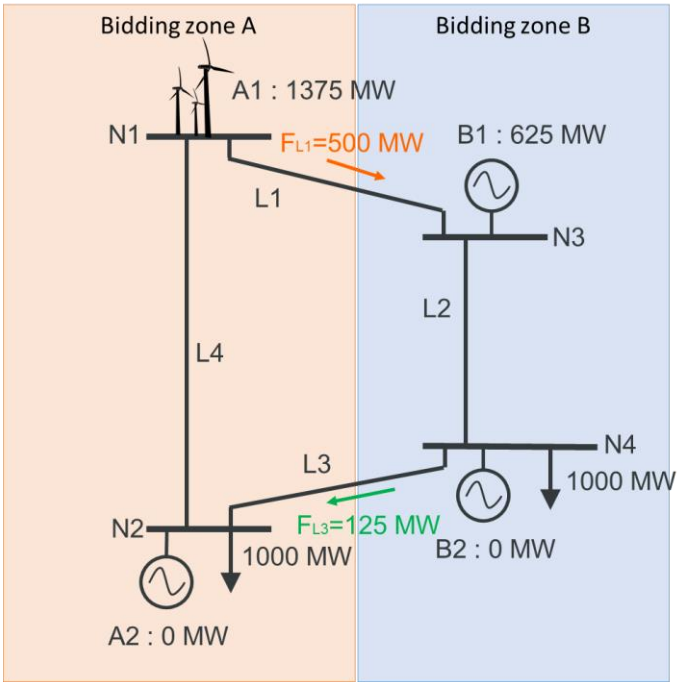

Figure 7-3: Output of market clearing

Figure 7-4 depicts the outcome of the step that follows the capacity allocation: TSOs assess flows inside bidding zones (lines L2 and L4). This reveals a **physical congestion** on line L2 which needs to be addressed through redispatching actions.

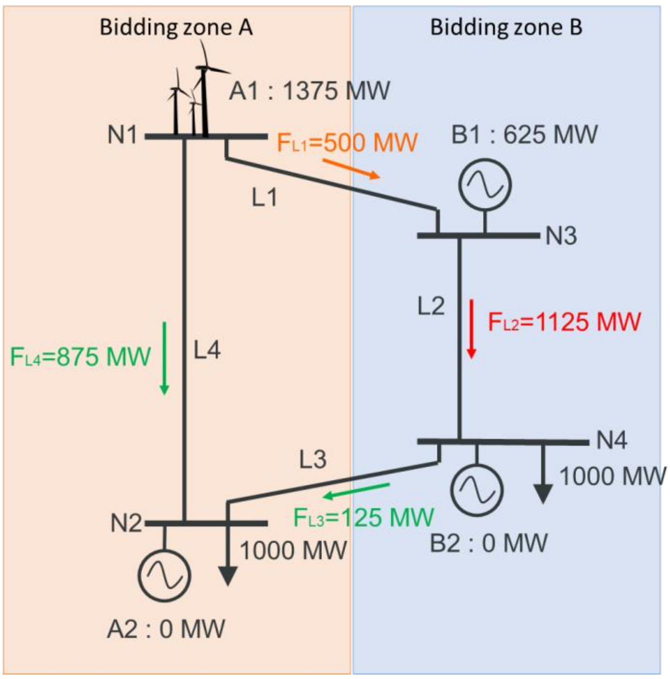

Figure 7-4: Post capacity allocation

The congestion is relieved by further reducing the production of A1 as well as the output of B1, to then turn on the next least-cost option, namely generator B2. As the thermal limit of line L2 is a binding constraint in the optimization of the redispatch, it can be classified as a **congestion** according to the Electricity Regulation.

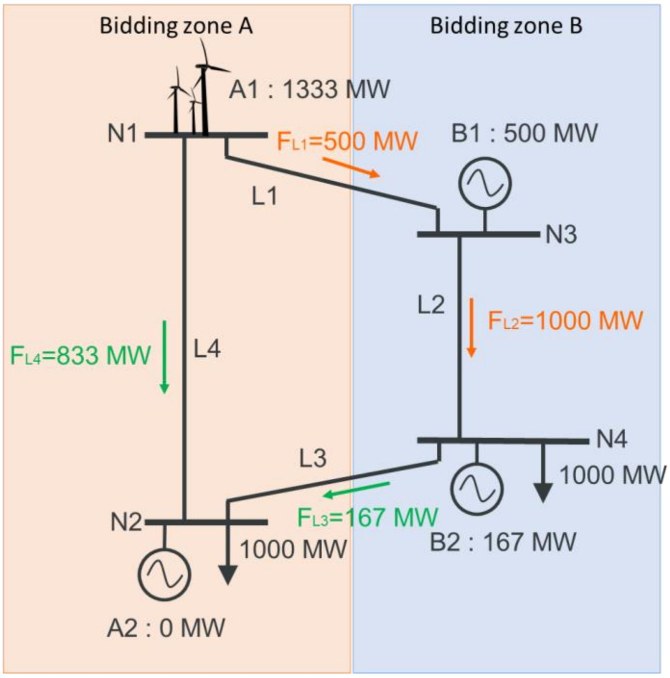

Figure 7-5: Output of redispatching actions

In conclusion, the examples show that **both a market and a physical congestion can lead to a congestion**. However, it is possible to have a **physical congestion (overload) after the market coupling without having a congestion (binding constraints) after redispatch**: for example, when two elements with different thermal ratings are connected in series, the smaller thermal rating will be binding after redispatch.

7.2 Survey of frequency threshold for structural congestions

As mentioned in Section 4.4, the Consultant (with the help of ACER) launched a survey to collect the opinion of experts in the field of congestion management regarding the current definition of structural congestion in the Electricity Regulation, with a particular focus on the concept of “frequency” and on a proper threshold of such attribute in order to clearly identify such congestions. The table below summarized the key figures related to the survey.

Number of respondents	31
Number of respondents who provided a figure	11
Number of respondents who provided a figure in the range 1÷20%	7

Table 7-1: Info on survey respondents

The fact that less than 30% of the respondents provided a proposition of threshold highlights the complexity of the topic. Indeed, this aspect was discussed broadly in the answers, as many mentioned that it would be appropriate to widen the scope of the definition of the structural congestion, to also include additional important elements, such as the impact on redispatch costs. It worth noting that the challenge of identifying a harmonized value that would be able to capture the needs and peculiarities of different countries. Moreover, it was claimed that the identification of structural congestions and the definition of the threshold should not be based only on historical data, but also on future forecasts based on system evolution. Finally, a common request of detailed consultation on the topic emerged.

All these remarks are valuable and represent an interesting starting point to initiate further discussions on the topic. We still consider important to lay the groundwork for beginning to improve the process of identifying structural congestions and, consequently, BZR. Clarifying the current definition and establishing a threshold on the issue of frequency needed to distinguish structural congestions from non-structural congestions is an important step in this direction.

Hence, the propositions of thresholds have been analyzed. The outliers (below 1% and above 20%) have been excluded from the values to be considered, also because not supported by strong justification. The key responses were instead in the range of 2÷20%, backed by considerations on existing statistics and impacts of different values. This is why the center of gravity of such range, namely 5÷10%, is here proposed as the starting point of a legislative process which will have to define the most appropriate value.

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