

## Article

# Coordinating Capacity Calculation via Electricity Market Coupling: Insights from the H2020 CROSSBOW Project

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**Abstract:** CROSS BOrder management of variable renewable energies and storage units enabling a transnational Wholesale market (CROSSBOW) is an EC-funded project, whose aim is to facilitate the shared use of energy resources by fostering cross-border management of variable renewable energies and storage units, enabling higher penetration of renewable energy sources (RES) whilst reducing network operational costs and improving economic benefits of clean energies and storage units. Towards these goals, CROSSBOW boosts regional cooperation among the system operators in South-eastern Europe (SEE), by deploying nine different tools to support the security coordination center (SCC) of the region. More specifically, the main CROSSBOW product, namely CROSSBOW Regional Operation Centre (CROSSBOW ROC) has proposed and demonstrated a set of functionalities for regional management and operation that enhance the existing regional structures, extending the capabilities of the already established Regional Security Coordinator (RSC) initiatives. Beyond enhancing RSC mandatory functions (including adequacy forecasts, coordinated security analysis, capacity calculations, and outage planning coordination), the ROC-BC product has developed new functions, linking the security considerations of involved TSOs with the operation of the fast-developing and harmonized electricity markets. In this paper, we investigate approaches for coordinated capacity calculation and cross-border trading via market coupling, developed within the ROC-BC product of CROSSBOW. Moreover, we present the final demonstration results as a part of ROC fundamental functionalities. Specifically, both net transfer capacity (NTC) and flow-based (FB) methods are examined and compared within a case study applying to the SEE region. The presented results demonstrate that the FB method exhibits better performance in all examined scenarios, considering three different key performance indicators (KPIs).

**Keywords:** CROSSBOW; H2020; ROC; RSC; coordinated capacity calculation; market coupling; ATC method; FB method



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## 1. Introduction

The European electricity sector is undergoing significant changes, including the regionalization of electricity markets and the integration of intermittent renewable resources that have resulted in increased and more volatile cross-border power flows [1,2]. These challenges have led transmission system operators (TSOs) across Europe to increase their coordination. According to the network code on operational security of ENTSO-E, each TSO should coordinate with the interconnected TSOs and report the current limits in terms of thermal rating and transitory admissible overload and voltage ranges [3,4]. Additionally, each TSO should inform all neighboring TSOs about its own system state and provide them

with additional information on the elements of its transmission network that are parts of the observability area of the neighboring TSOs [5].

In that context, TSOs have been developing Regional Security Coordination Initiatives (RSCIs) and have adopted a multilateral agreement in 2015 to make participation in RSCIs mandatory for TSOs [6]. The main objective of an RSCI is enhancing the regional coordination of system operation activities by providing services to TSOs. The EU network codes have institutionalized RSCIs in the legal framework through the creation of so-called regional security coordinators (RSCs). Moreover, in its “Clean Energy for All Europeans (2016 Commission)” legislative package, the Commission has proposed to further increase regional operations and cross-border cooperation within the internal electricity market for electricity (IEM) [7–10]. Specifically, the proposed electricity regulation introduces the creation of regional operational centers (ROCs) that follow the framework established for RSCs. ROCs should carry out defined tasks of regional relevance and should have the power to adopt decisions and make recommendations to national TSOs. The concept behind ROCs was to enhance security of supply and drive cost reductions through more efficient system operation, reduced need for investment, and the cost-effective integration of renewables. Thus, the benefits of regional cooperation, particularly in a system with a significant share of variable renewables, are well documented in Europe and in other jurisdictions. In addition, increased TSOs coordination can help to increase the overall reliability and reduce the costs of achieving that level of reliability and thus achieving the Energy Union’s goals of reliable, affordable, and sustainable energy [11,12].

However, the establishment of centers for regional cooperation among different TSOs is not an entirely new concept. A number of RSCs have been developed in the past, including CORESO in Western Europe, TSCNET in Central Europe, SCC in the Balkan region, NORDIC in the Nordic region, and Baltic RSC in the Baltic region. The last paradigm of such a coordination center is the establishment of SEleNE in Thessaloniki (Greece). The establishment of regional cooperation through RSC is strongly supported by ENTSO-E [11,12]. The role of these centers has mainly been acting as an advisory and supporting body for the individual TSOs. RSCs are service providers and were not built with live system operation and control capabilities [13]. In other words, they make recommendations that individual TSOs in most cases follow but each TSO can deviate from if required for ensuring the security of supply. This is an essential aspect because it allows RSCs to sustain light and efficient structures and it limits the need for regulatory oversight and harmonization.

As such, their services and functionalities are mainly associated with short- and medium-term coordination of the transmission network in the respective region and not with the long-term planning, which remains a responsibility of the individual TSOs’ control centers. In the multilateral agreement [13–15] that all ENTSO-E members have signed, RSCs must carry out the five following core services:

1. Improved individual grid model (IGM)/common grid model (CGM) delivery: validating forecasts of the individual TSOs’ grid models, sharing them with each other and merging them to a common grid model.
2. Coordinated security analysis: evaluating the consequences of contingencies in the interconnected grid and simulating remedial actions including coordinated ones.
3. Coordinated capacity calculation: determining available capacity for cross-border trading while ensuring the security of the grid.
4. Outage planning coordination: coordinating planned outages on equipment with cross-border influence to avoid security issues.
5. Short-term adequacy forecasts: assessing the adequacy of the grid in the short term.

The way TSOs use the inputs from RSCs to operate their grid differs between these five core services. For example, for coordinated security analysis and outage planning coordination, RSCs perform regional calculations that are important to the TSOs’ decision-making, but TSOs still need to consider several other national factors not captured by regional calculations. The final operational decision-making by the national TSO cannot be delegated. On the other hand, for the other three core services (coordinated capacity calcula-

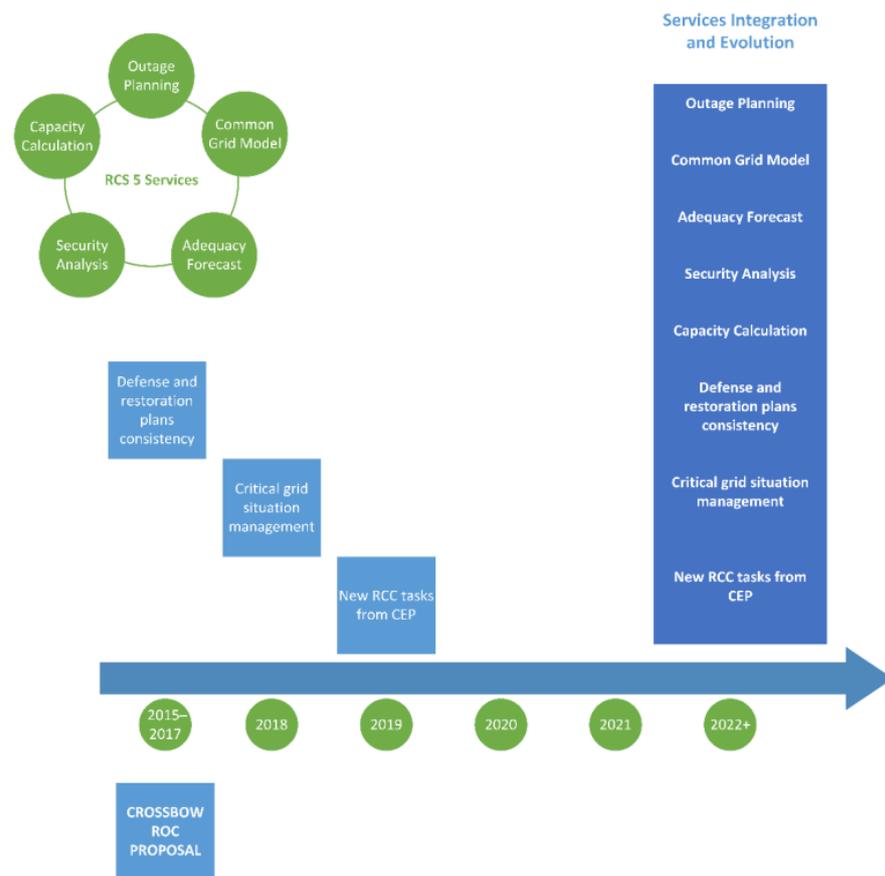
tion, short-term adequacy forecasts, and individual and common grid model delivery), the results stemming from the regional calculations constitute sound products on which many TSOs and market parties can robustly base their decisions. The decision-making power of the TSOs in such joint regional calculations consists largely of checking for errors and giving authorization for the calculation results to be used (e.g., for the calculated capacities to become the basis for allocation of congested interfaces) [13,14].

The Commission's proposal (2016 Clean Energy Package) places an obligation on ENTSO-E to develop a methodology for identifying regional crisis scenarios and to undertake the analysis, with the option to delegate the entire analysis or individual tasks to the ROCs [11–13]. ROCs have the regional knowledge, necessary expertise, and analytical capability that allow them to identify regional crisis scenarios more effectively than ENTSO-E or individual Member States. In undertaking this task, ROCs should coordinate closely with ENTSO-E and other ROCs, as risks can be cross-regional (e.g., severe weather events can, in unusual cases, have similar adverse impacts on more than one region at the same time, as happened in January 2017). ROCs could also play a key role in responding to actual crisis events. Properly equipped ROCs have all the information available to understand the scope and scale of the crisis and be best placed to coordinate responses. This is evidenced by the events of November 2006, which nearly led to a total European blackout as many individual TSOs did not initially realize that Europe's transmission grid had split into three separate synchronous areas [11,12].

Another example is the event that took place on 8 January 2021 at 14:05 Central European Time. During this event, the Continental Synchronous Area in Europe was separated into two areas (the northwest area and the southeast area) due to the tripping of several transmission network elements. The system separation resulted in a deficit of power in the northwest area and a surplus of power in the southeast area, leading in turn to a frequency decrease in the northwest area and a frequency increase in the southeast area. Even though the communication, coordination, and resynchronization were successful and timely, this event can be used to identify further improvements in coordination and communication between TSOs for large-scale events. Procedures for the management of balancing platforms during system events should also be developed to avoid any unintended consequences which could lead to a larger disturbance of the system. The European Awareness System was used successfully during the event, but more functionalities should be developed to further assist TSOs in the sharing of operational data (pre- and post-fault) and coordinated actions. Finally, coordination of regional restoration could be enhanced if it is deemed necessary by TSOs [11,12].

In Figure 1, a chronology on deploying of regional cooperation is given in an illustrative way. One can see that today's RSCs certainly provide the five standard operational services—common grid model, coordinated operational planning, security analysis, outage planning coordination, short- to medium-term adequacy forecast, and coordinated capacity calculation. In the next decade, the consistency check of TSOs system defense and restoration plans will be transferred from RSCs to regional coordination centers (RCCs), and TSOs will identify the management of critical grid situations [6,11,12].

According to EU Regulation on the internal electricity market (2019/943), RCCs should be established in the timeframe 2020–2024, evolving from RSCs experience as required. As we understand, RSCs are service providers to TSOs, with staff and budget coming from TSOs. RSCs can develop their services as much as is needed to make grids more efficient. The evolution of regional coordination is moving from RSCs to ROCs and soon to RCCs with the key point being the more efficient and coordinated regional operation of the TSOs. In addition, the existence of regional operation centers (ROCs) is covered by the introduction of RCCs, but all the knowledge and new elements of ROC will be delivered to the new coordination centers.



**Figure 1.** Chronology of regional cooperation.

The introduction of ROC-BC, under the umbrella of the CROSSBOW project, broadens the scope and the functionalities of the coordination centers. As mentioned, the CROSSBOW ROC product has been created and been demonstrated in a period where ROCs proposal was under consideration for adoption at the EU council and was leading to a more efficient coordination of the TSOs in the region. However, the ENTSO-E's proposal for RCCs in 2021 [13] has accelerated the evolution of the RSCs. One of the novel responsibilities of ROC is the cross-border capacity calculation mechanism and the monitoring of the regional wholesale electricity market that is established.

Cross-border interconnections are one of the most potent methods for overcoming some of the technical issues that come with large-scale renewable energy integration. Neighboring countries can trade several reserve resources, assisting one another in dealing with the growing balancing requirements. Besides that, the risks associated with demand–supply imbalances can be diversified due to the natural diversity of generation and demand conditions in different countries, as well as varying weather conditions, generation mix, and demand portfolios, substantially limiting the total balancing needs [16,17].

Furthermore, interconnections are essential in terms of the integration of national electricity markets. To begin, an appropriate method for coordinated capacity calculation is necessary, which must be in accordance with the ENTSO-E network codes for capacity allocation and congestion management (CACM) and System Operation Guide Line (SOGL). The construction of a cross-border balancing mechanism is the second challenge related to cross-border power transfers. Such a method may include imbalance netting, automatic frequency restoration reserve (aFRR), manual frequency restoration reserve (mFRR), and replacement reserve, according to EU network rules [6,15].

In this paper, we focus on this basic ROC functionality; cross-border capacity calculation via electricity market coupling. To address this, we employ two methods that are widely used in literature, namely, the net transfer capacity (NTC) and the flow-based

(FB) ones [18]. Both methods are based on a wide-area optimization procedure, with a common objective function and different constraints to be taken into consideration. The mathematical modeling of both methods has already been included in detail in our previous work [19,20] and the first results have been presented there. The case study of the SEE region has been selected as a special one for the CROSSBOW project and for our tests, where the market procedures and coupling is still at a preliminary phase. The novel contribution of this paper is the scalability of both approaches, expanding them in time and place, instead of the algorithms themselves. Those methods are applied in several extended test case scenarios for three, four, and five countries' market coupling and for a time period of a month. These new results of the CROSSBOW final demonstration phase verify the preliminary ones [19,20], while a sensitivity analysis gives insights regarding the applicability and efficiency of both cross-border trading methods. Finally, this new analysis conducted gives some metrics of comparison between two methods in order to derive a solid conclusion on which method is more beneficial for the examined region.

The rest of the paper is organized as follows: In Section 2, an overview of the CROSSBOW ROC product and its functionalities are described, giving special attention to coordinated capacity calculation via NTC and FB methodologies. In Section 3, the methods and the results of electricity market coupling, which are obtained by both approaches for the SEE region scenarios tested, are presented with a comparative approach, and in Section 4, the conclusions give us the opportunity to summarize the key points and benefits.

## 2. Methodological Framework

To realize ambitious targets of RES integration within a modern and unified European market framework, an ROC is fundamental. Its scope includes all TSOs in the region working together to gain benefits from a more effective approach to the various challenges facing system operators. The ability to handle challenges from a regional perspective enables the grid to operate more efficiently and reliably, taking advantage of economies of scale for its generation assets, and coping more effectively with the various uncertainties (renewable energy stochasticity, load fluctuations, unpredictable incidents, etc.) [14,21,22].

In this frame, CROSSBOW proposes an integrated approach to manage and operate the transmission network in SEE region. Toward that end, TSOs' actions will be closely coordinated. The project has two main directions in regional coordination. The first one; by advancing the supporting data collection, data exchange, calculation, and optimization methods, CROSSBOW is demonstrating how to enhance the five core services available from RSCs today. The second one; by defining and incorporating new services (beyond the five core services) associated with short-term operational tasks, CROSSBOW demonstrates how RSCs can evolve. Among these services are imbalance management, congestion management, and voltage management, all of which fall under the purview of individual TSOs.

To achieve this integrated approach, it is critical to establish an ROC that is responsible for coordinating the management of the entire transmission system in SEE efficiently and securely as well as enabling the sharing of resources. As one of the main products of the CROSSBOW project, this ROC is of primary importance. The CROSSBOW ROC product has been designed to be a very heterogeneous product, incorporating a variety of functionalities that relate to the business processes of RSCs. ROC provides improvements to some RSC functions, but also defines and incorporates new services associated with short-term operations that RSCs cannot currently provide.

In order to ensure that the developed functionalities of this product are available to other RSCs in Europe, special attention was given at the development stage to the stakeholders of this product who are located in the European region. Additionally, it serves as a catalyst for the integration of regional balancing markets by providing the necessary toolkit. More specifically, CROSSBOW ROC incorporates the following operational functionalities:

1. Probabilistic approach for regional adequacy assessment in SEE region;
2. Real time quality check of common grid models;
3. Enhance method for PNP estimation;

4. Dynamic line rating forecast for overhead lines;
5. Determination of capacity calculation input data;
6. Cross-border congestion FB algorithm;
7. Cross-border congestion NTC-based algorithm;
8. TSO FR reserve probabilistic sizing using reserves offered from another TSO via interconnections;
9. IGM quality assessment;
10. Enhanced transmission system resilience during emergencies;
11. Over and under-frequency real-time control scheme using PMUs [23].

### 2.1. Coordinated Capacity Calculation for Cross-Border Trading

The interconnection lines among national transmission systems were originally intended to assure steady operation and assist in the event of system failures within the interconnected system. Cross-border trading places an enormous additional strain on interconnection lines, causing network congestion and thereby restricting power trade [24]. Congestion occurs when the demand for electrical energy transfer exceeds the transmission system's capacity, i.e., when uncontrolled usage of the network might jeopardize the system's security [25,26].

According to the CACM, the term "congestion" can be classified into [6]:

- (a) "Physical congestion", which implies any network condition when forecasted or realized power flows violate the thermal limits of the grid elements and the voltage stability or the angle stability limits of the power system.
- (b) "Structural congestion", which implies 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.

Congestion control measures have been established to avoid the transmission system from being overloaded by cross-border energy flows and the resulting risk to the grid's security. Congestion management also includes the distribution of rights to transfer electricity to other countries via a transmission network connecting them, which is vital to cross-border trade.

Electricity trading takes place in multiple sequential markets to ensure an exact balance between supply and demand. To that purpose, forward and future markets are followed by a day-ahead and intra-day market, which is then followed by a final real-time imbalance settlement [27,28]. Traditionally, energy markets were regulated at a national level, with each country focusing on electric power supply self-sufficiency. The target model for electricity trading in the EU is based on these foundations and uses a zonal approach to build on several interconnected markets. Electricity can be freely exchanged inside each zone, with little or no concern for network restrictions. In cross-border trade, though, the interconnection capacity with other bidding zones is considered during the trading process [29].

A coordinated capacity calculation and allocation method are required for cross-border electricity trading. Because energy flows are not only constrained by financial commitments, but also by physical laws, stronger cooperation among market areas is also necessary. The purpose of a coordinated capacity calculation process is to ensure that the available transmission capacity is allocated efficiently. Offering cross-border transmission capacity to the market must be balanced against ensuring the electricity system's reliable functioning. The method for calculating available trading capacity has a significant impact on the market [6,30,31].

In general terms, the capacity calculation procedure takes place in two different time frames:

1. (TSOs) coordinate long-term capacity calculation for the year- and month-ahead market time frames to guarantee that capacity calculation is accurate, and that adequate capacity is made available to trade. Coordinated long-term cross-region capacity

allocation regulations necessitate the development of a common regional allocation scheme. RCCs are in charge of it, and it is necessary to predefine a mechanism for allocating long-term capacity in a coordinated manner across several longer timeframes within the respective region.

Mechanisms for operational security constraints and contingencies must be included in the solution for a standard capacity calculation methodology. A common grid model methodology is agreed upon and established among involved TSOs, while security analysis based on multiple scenarios is applied. All involved TSOs in the region capacity calculation jointly develop a common set of scenarios to be used in the common grid model for each timeframe. TSOs agree on and develop a standard grid model methodology, and security analysis based on various scenarios is used. For every time window, all relevant TSOs in the region capacity calculation produce a common set of scenarios to be used in the common grid model.

For the purpose of allocating forward capacity, the TSOs need to determine what amount of capacity should be given on a long-term premise and what percentage should then be allocated on a different long-term one. Following long-term allocations, the remaining available capacity is offered on a short-term basis.

2. The term “short-term capacity calculation” involves a combination of day-ahead, intraday, and balancing timescales in which the relevant TSOs should estimate available capacity in a coordinated way. They should also utilize a single grid model for this, which includes forecasts on supply, demand, and network status for each hour.

The method for providing generation and load data to TSOs defines which production units and loads are required to give data to their relevant TSOs for capacity calculation. The available capacity is then calculated according to the algorithm considered. The available cross-border capacity is among the critical aspects of the subsequent calculation process, whereby all regional bids and offers are collected and matched in an economically effective way, considering available cross-border capacity.

Each of the TSOs in the area of consideration ensures that capacity is adjusted according to the last available data within each market time window. The frequency of this adjustment is determined by operational efficiency and security.

Thus, the steps included in the capacity calculation procedure are as follows:

- The methodology for determining the interconnection lines’ reliability margin.
- The methodology for calculating operational security bounds, contingencies relevant to capacity calculation, and allocation constraints.
- The methodology for determining remedial measures to be taken into account when calculating capacity [14].

## 2.2. NTC Methodology on Cross-Border Electricity Trading

The capacity calculation methodology is either a coordinated NTC algorithm or the FB one. According to the network code on CACM, the future calculation and market design for the European day-ahead and intraday markets may be either based on the FB or the NTC approach [30–32]. However, the CACM requires that “TSOs may jointly request the competent regulatory authorities to apply the coordinated NTC approach if the TSOs concerned are able to demonstrate that the application of the capacity calculation methodology using the FB approach would not yet be more efficient compared to the NTC approach and assuming the same level of operational security in the concerned region”. It is not assumed whether either the FB or NTC method is efficient in the SEE region since this will be investigated. The better the representation of the grid is in the energy market, the more accurately the TSO can feed physical constraints into the price calculation algorithm. The motivation behind introducing FB is that it has the potential to better account for the physical flow and constraints compared to the widely used NTC method. A better representation gives a better chance of optimizing the utilization of the scarce transmission capacity, which should lead to more accurate price signals and increased social economic welfare.

On the one hand, the coordinated NTC method considers that electricity can flow through different interconnection lines based on various predetermined arrangements that enable the safe and reliable operation of the interconnected electricity network, as defined by the relevant TSOs. The coordinated NTC method is a capacity calculation method that works on the premise of assessing and defining a maximum energy exchange across neighboring bidding zones in advance. The NTC approach should only be used in areas where capacity is less interdependent and where the FB one cannot contribute or enhance the existing solution.

To proceed with the NTC calculation, the N-1 criterion is used to evaluate system security. It defines a level of security where the power system can handle the outage of any one single individual component (i.e., a transformer, a line, a production unit). The following limiting considerations must be addressed when estimating transfer capacities with respect to the N-1 criterion: (a) thermal constraints, (b) voltage limitations, and (c) rotor angle stability limitations. The total transfer capacity (TTC) is defined as the “maximum between two areas compatible with operational security standards applicable at each system provided future network conditions, generation, and load patterns were perfectly known in advance”. As a result, TTC is always linked to a specific power scenario, such as a generating schedule, consumption pattern, and available network, all of which are used to construct a mathematical model of the power system (load flow equations). The solution to this model reveals the voltages at network nodes and power flows in network elements, which are monitored by a TSO in order to determine the system security. This model’s solution is known as the “base case”, and it serves as the starting point for TTC computation [18,30,31].

The forecast uncertainties of the power system state, for a given time period in the future, may decrease according to the selected time frame. The transmission reliability margin (TRM) is “a security margin that copes with uncertainties on the computed TTC values arising from:

1. Unintended deviations of physical flows during operation due to the physical functioning of load-frequency regulation;
2. Emergency exchanges between TSOs to cope with unexpected, unbalanced situations in real time;
3. Inaccuracies, e.g., data collection and measurements” [30,31].

On this basis, NTC is the maximum exchange between two areas compatible with security standards applicable in both areas (N-1 criterion) and taking into account the technical uncertainties on the future network conditions. NTC may be allocated in different time frames to match the need for securing longer-term trading and to provide room for shorter-term trading after extensive load flow studies performed by the TSOs. When determining the NTC on the interconnection between two countries, the involved TSOs on each side calculate the capacity, using the lowest value of the two [30,32].

Considering energy trading, the TSOs will order the transactions according to the priority rules of the allocation process until there is no more transfer capacity. In parallel new information on weather, topology, etc., helps not only to distinguish the “already allocated” from the “still available” capacities, but also allows simulation of the coupling effects between NTCs across the ENTSO-E regions. That is, if all data has been exchanged between market participants and TSOs, the accuracy of the ex-ante calculations of transfer capacities becomes better as real-time operation is approached. On a strict confidentiality basis, TSOs may require from market participants the planned generation schedules (e.g., on a day-ahead basis) which will result in load flows over the cross-border lines. These are called notified transmission flows (NTF) [31,33]. The NTF can be interpreted as the already nominated part of NTC by the already accepted contracts at the studied time frame.

As the booking/allocation process proceeds, the new information on generation schedules, which becomes available to the TSOs, will allow them to update their load flow calculations in order to refine their assessment of security problems. As a result, TSOs will evaluate the remaining available transfer capacity (ATC) between systems. The ATC is

“the transfer capacity remaining available between two interconnected areas for further commercial activity over and above already committed utilization of the transmission networks” [30–33]. For the calculation of ATC daily, the TSOs ought to take into account the firm rights from previous time frame calculations.

In terms of an NTC market-clearing algorithm, the methodology finds the optimal solution for power exchange based on given capacities and bids from market participants. The algorithm is a linear constrained optimization algorithm, with an objective function of maximizing social welfare. The constraints are the NTCs between the bidding areas supplied by the TSOs. Nevertheless, only the commercial exchanges between bidding areas are considered in the market-clearing algorithm, and it is assumed that the power will take the shortest path from production to consumption. In practice, the power distributes itself through the whole grid according to physical laws applied to the characteristics of the grid and the situation in the entire power system at any time. When transferring power between two nodes, flows occur on parallel paths also connecting the two nodes. The flows induced on the parallel paths are called loop flows. The loop flows, in addition to losses in the lines, are not accounted for by the market algorithm, and are therefore left to the TSOs to manage [18,34].

### 2.3. FB Methodology on Cross-Border Electricity Trading

The better the representation of the power grid is in the energy market, the more accurately the TSO can channel physical constraints into the market-clearing algorithm. The motivation behind introducing FB is that FB has the potential to better account for the physical flow and constraints compared to the widely used NTC method. A better representation offers a better chance of optimizing the utilization of the transmission capacity, which should lead to less deviations in market-clearing prices and increased social economic welfare [14,20,35,36].

The FB calculation algorithm is a method for optimizing the available capacity in highly interconnected networks by taking into account the fact that power might flow through multiple tie lines. Energy exchanges between market zones are restricted by power transfer distribution factors (PTDFs) and availability margins on critical network elements (CNEs) or critical branches (CBs). When capacity between market zones is highly interrelated, the FB approach should be used as the primary methodology for calculating day-ahead, intraday, and balancing capacity [34,35].

In the FB approach, the physical network constraints are considered [37–39]. That means that the capacity allocation is realized partially, ex ante the market clearing and partly at the same time with the market clearing [18]. All CBs of the electricity grid are considered in the N-state and in critical N-1 states. The flow via a CB is restricted by the remaining available margin (RAM), while the correlation between NPs and flows through CBs is reflected in the sensitivity factors PTDFs. By incorporating the PTDFs, there are fewer limitations to the solution domain, and one obtains a better utilization of the system. The PTDFs are obtained from the AC power flow equations through a DC power flow representation of the power electricity grid [35–37,40].

The RAM and PTDF values are defined, ex ante the market clearing, by the TSOs, and then these values determine the flow domain. Each boundary of the FB flow domain refers to the limit of a CB. In the FB method, the transit flows are taken into account internally in the market. Therefore, all commercial exchanges have to bid for the transmission capacity, including transit flows. This internalization considered in the FB approach gives a more efficient transmission capacity management, at least from a theoretical point of view [34,36].

The RAM is essentially the available line capacity in the day-ahead market. There are two primary phases in the RAM technique. At first, the CBs and critical outages (COs) must be identified. In the second phase, the RAM is calculated for these CBs under the COs. For each CB, the highest power flow that is permitted is determined based on the thermal limit of the line. After that, the RAM is calculated as the highest allowable power flow, which is restricted by three factors [18,36,37]:

1. The commercial trades outside of the day-ahead power exchange (i.e., bilateral trading, forward markets, intra-day markets, and real-time balancing) produce the reference flow: these trades can be internal or external (inside a market zone or across market zones).
2. The final adjustment value (FAV): the FAV allows TSOs to consider extra information, such as an additional margin owing to complicated remedial activities or active topology control; the FAV can be positive or negative.
3. The flow reliability margin (FRM): the FRM is a safety margin that must be used to indemnify for the approximations made in the FB method such as the assumptions for PTDFs, accidental flow deviations owing to load frequency control, and the use of a linear grid model with a simplified topology [20,36–38].

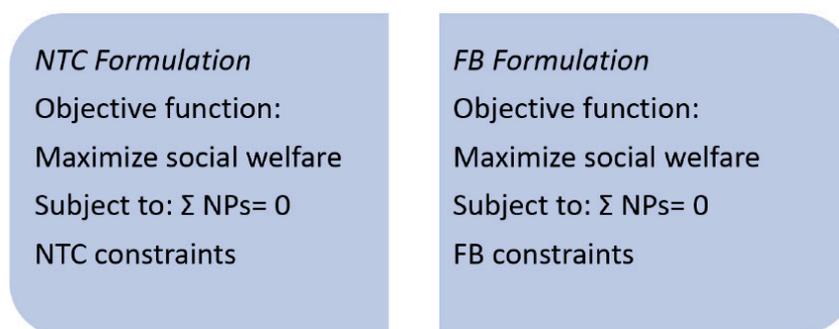
The FB market coupling process consists of three main parts, namely, pre-market coupling, market coupling, and post market coupling. The pre-market coupling process starts on the evening two days before the physical delivery of the energy traded [36,38]. As mentioned above, two fundamental parameters are deployed for the FB optimization algorithm: the PTDFs and the RAM. The FB parameter calculation started two days before the delivery day (D-2) and completed the day-ahead morning. However, the day-ahead market results must be known already for the calculation of the PTDFs and the RAM. The solution that is given in this problem is the following: the PTDFs and the RAM values are defined on the basis of a forecast of the power system's state, at the time of the delivery (i.e., the D-2 forecast). Therefore, the accuracy of the predicted values is not only crucial for the maximization of the social welfare from an economic point of view, but also for the secure operation of the transmission system. Afterwards, these FB parameters are delivered to the algorithm for the day-ahead market clearing [18,20,36,37]. The market coupling phase is carried out by the power exchange. The results, such as net positions and prices, are provided to the market. During the post-market coupling process, the TSO verifies the market results, analyzes the operational security, and deals with the congestion rent [36,40].

#### 2.4. Basic Steps of Our Work

As mentioned, the NTC current market-clearing design only considers commercial exchange between the market bidding zones. Since NTC does not account for physical constraints, actual power flows may differ from market power flows. Opposite this, the FB methodology considers the physical laws of the network by integrating them as part of the optimization problem in the form of optimization constraints. This denotes the main difference between the NTC and FB approach. By implementing the flow-based methodology, one creates market solutions closer to physical reality as well as respecting the operational security of the grid.

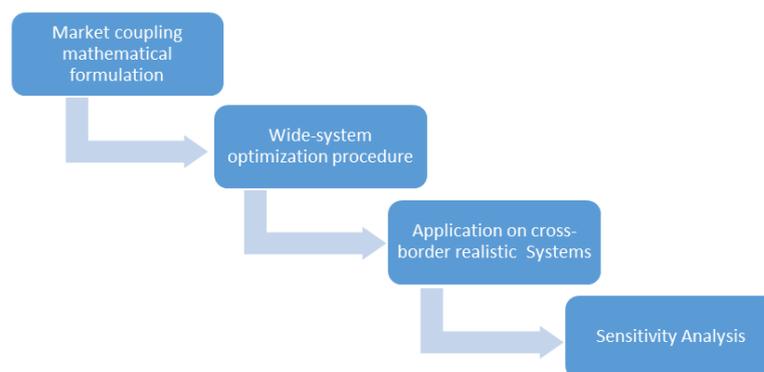
As mentioned in the introduction, the mathematical background for both the NTC and the FB algorithm was presented in detail in [19,20]. Briefly, the problem is formulated under mathematical terms as an optimization problem, by a common objective function for both the NTC and FB approaches. The main difference is found in the constraints established on the problem formulation.

Both algorithmic approaches are investigated. The objective in both methods is to maximize the social welfare of the electricity market. This differentiation is depicted in Figure 2 (where NP (net positions) = supply – demand). The FB algorithm, in most cases, leads to a better solution than the NTC, in terms of social welfare, price convergence, and trading opportunities. The reason behind this is the difference in the constraints, which lead to a wider solution space for the optimization problem. Thus, for a given level of safe operation, the boundaries of FB domain will always be located on or outside the boundaries of NTC domain.



**Figure 2.** Formulation of the NTC and FB algorithm.

Nevertheless, in this work, we emphasize the scalability of both methods instead of the algorithms themselves. The basic concept of our work on the market coupling methodologies, with both algorithms, is illustrated in Figure 3.



**Figure 3.** Basic concept of our work on electricity market coupling via NTC and FB approaches.

### 3. Case Studies in SEE Region

In the context of the ROC product developed under the umbrella of CROSSBOW, we had the responsibility to apply both NTC and FB methods on coordinated capacity calculation and cross-border electricity trading via market coupling in SEE. The case study of the SEE region is selected. The rationale behind this choice was the fact that the market coupling in this area is in the early stages, and any analysis regarding cross-border trading would benefit the regional electricity market. The first results of this case study have been already presented in our previous work [19,20] where our analysis considers only a typical day as time period and only the cross-border transmission lines as CBs, between the markets coupled. Nevertheless, the final demonstration phase has just finalized, and the new results obtained by extended test case scenarios verify the preliminary ones, while a sensitivity analysis gives some insights regarding the applicability and efficiency of both cross-border trading methods.

To cover a wide range of cases we chose a period of a month to test both NTC and FB algorithms and a sufficient number of countries within the SEE region. To conduct our experiments, a typical month has been chosen, namely, June 2019. The participating countries in this regional market, in the form of TSOs, are five countries, namely, Greece, North Macedonia, Bulgaria, Serbia, and Romania. The input data were retrieved from several sources. Specifically, the market data (sell and buy bids) for each market are simulated very close to real values, retrieving public data from the involved TSOs (ADMIE/IPTO, MEPSO, ESO, EMS, and Transelectrica using ENTSO-e transparency platform). The network data used for both NTC and FB methods, i.e., NTC margins, AMF margins, critical branches (CBs), PTDF values, and common grid model, are real and are provided by the involved TSOs and SCC for the entire SEE region.

In these final demonstration tests, more CBs from the involved countries were included, and the extended time interval enhanced the quality of the experiments. Specifically, all the cross-border lines between the five countries, plus some internal lines of ESO (Bulgaria) and MEPSO (North Macedonia) after their suggestion, were considered as CBs. The typical days selected are all Wednesdays of June 2019, for procedural reasons, as suggested by SCC, the coordination center of the region.

After the deployment, testing, and demonstration of the NTC and FB algorithms for a three-country scenario (Greece, North Macedonia, and Bulgaria), four-country scenario (Greece, North Macedonia, Bulgaria, and Serbia) and five-country scenario (Greece, North Macedonia, Bulgaria, Serbia, and Romania) in SEE region, we obtain augmented conclusions on:

- (a) The maximization of the social welfare;
- (b) Better trading opportunities;
- (c) The price convergence.

Based on these benefits, a quantitative assessment of both NTC and FB results is given via three indexes, namely the social welfare (*SW*), market coupling capacities (*MCC*), and price convergence (*PC*) index. The definitions of these three indexes, which practically are the key performance indicators (KPIs) of the capacity calculation via electricity market coupling, are calculated as follows:

- **Social welfare index**

$$SW = \frac{[Social\ Welfare\ with\ market\ coupling - Social\ welfare\ without\ crossborder\ trading]}{Social\ welfare\ without\ crossborder\ trading} \cdot 100\% \quad (1)$$

- **Market coupling capacities index**

$$MCC = \sum_{c=1}^k \sum_{l=1}^n Market\ Coupling\ Capacities \quad (2)$$

where *c* represents the countries participating in the market coupling and *l* the cross-border interconnections or lines.

- **Price converge index**

$$PC = \max(p_i) - \min(p_i) \quad (3)$$

where *p<sub>i</sub>* is the price vector of the countries involved in cross-border trading via market coupling.

- **Total performance index**

$$TP(\%) = SW(\%) \cdot |PC(\%)| \quad (4)$$

where *SW*(%) is the *SW* index and the

$$PC(\%) = \frac{[PC\ with\ market\ coupling - PC\ without\ crossborder\ trading]}{PC\ without\ crossborder\ trading} \cdot 100\% \quad (5)$$

The overall results and the KPIs values are recorded in Tables A1–A5 (Appendix A), for all test cases. In all examined scenarios, the comparison between the two methods demonstrates that the FB approach facilitates cross-border trading since it creates an efficient cross-border electricity market that offers increased benefits for the participants. Particularly, the FB method offers enhanced utilization of the interconnection lines for all the scenarios tested, since the calculated market coupling capacities are higher than the respective derived from the NTC algorithm. The total social welfare shows a significant increase with the FB approach, which is an important economic benefit for all participants involved in the market. Finally, it should be pointed out that the more the countries are coupled, the more the overall welfare gain is, as expected, mainly via the FB method.

Another benefit of this comparison is the enhanced price convergence. The prices converge clearly better via the FB method for three, four, and five countries.

However, for reader convenience, the indexes obtained from the five-country scenario by both the NTC and FB algorithm are presented in Figures 4–6, where one can observe the comparison between the two methods that is mentioned above, in a more illustrated way.

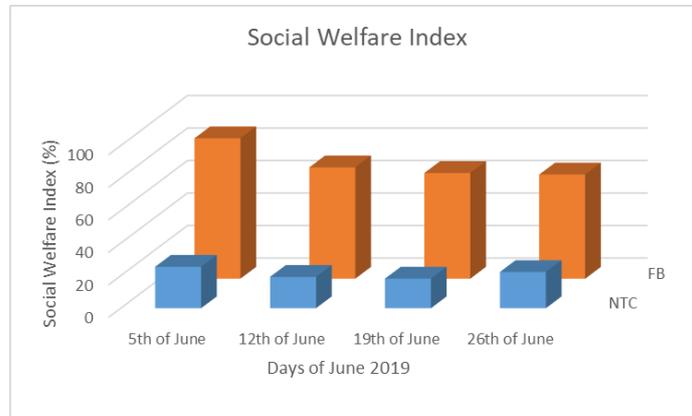


Figure 4. Social welfare index for the five-country scenario via both approaches.

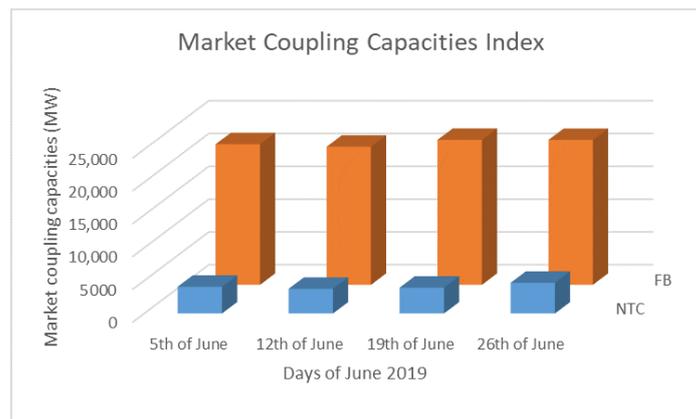


Figure 5. Market coupling capacities index for the five-country scenario via both approaches.

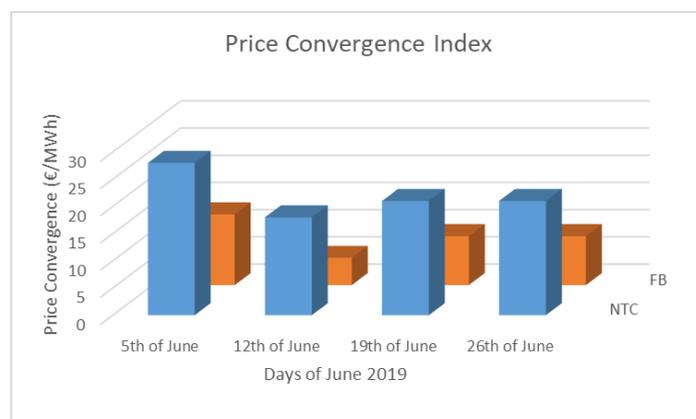
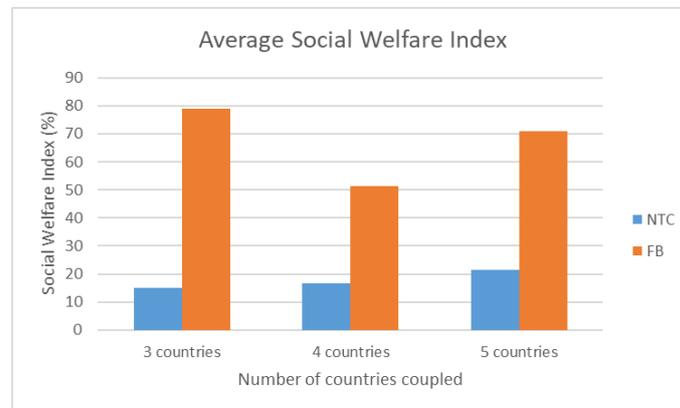


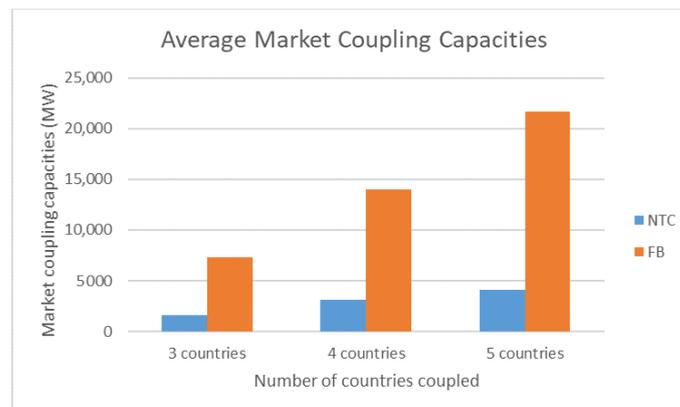
Figure 6. Price convergence index for the five-country scenario via both approaches.

To further clarify the overall results obtained via both market coupling approaches in SEE region during June 2019, an average range of each index is considered. Thus, in Figures 6–8 the average score of SW, MCC, and PC indexes are depicted for the three-, four-,

and five-country scenarios, respectively. Specifically, in Figures 7 and 8, it is easily observed that there is an important increase in the average SW and MCC index via the FB approach compared with the ones obtained via the NTC method for different numbers of countries.

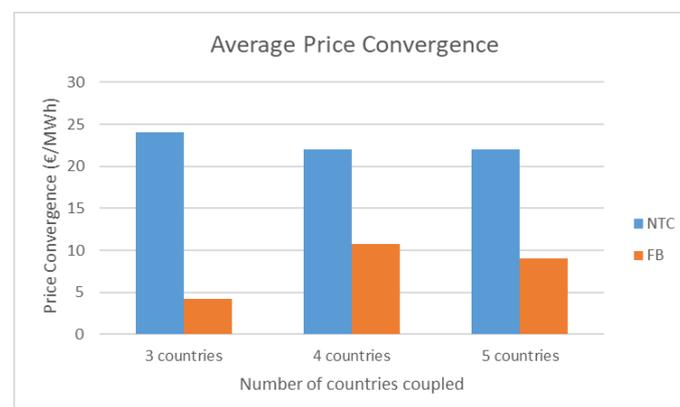


**Figure 7.** Average social welfare index via both approaches.



**Figure 8.** Average market coupling capacities index via both approaches.

In addition, in Figure 9, one can observe that the prices converge clearly better via the FB method for three, four, and five countries. The price convergence index is of great significance since the optimization procedure is realized for both approaches in a wide-region concept, resulting in similar final prices for all markets involved. As a general conclusion, in all the scenarios tested, the overall benefits resulted from the FB approach seem to be greater than the NTC one.



**Figure 9.** Average price converge index via both approaches.

At this point, it should be noted that as expected, the more the countries are coupled, the more the total social welfare in euro is, even though the average SW index appears to be higher for the three countries scenario via the FB method. This is illustrated in Figure 10. Furthermore, the average PC index is calculated as the lowest one in the three countries scenario with the FB method, in all the time frames. The reason why is that for the examined three countries scenarios, all the cross-border lines, plus some internal lines of ESO (Bulgaria) and MEPSO (North Macedonia) have been considered as CBs, given that they are with ADMIE/IPTO (Greece) the three TSOs involved in these scenarios.

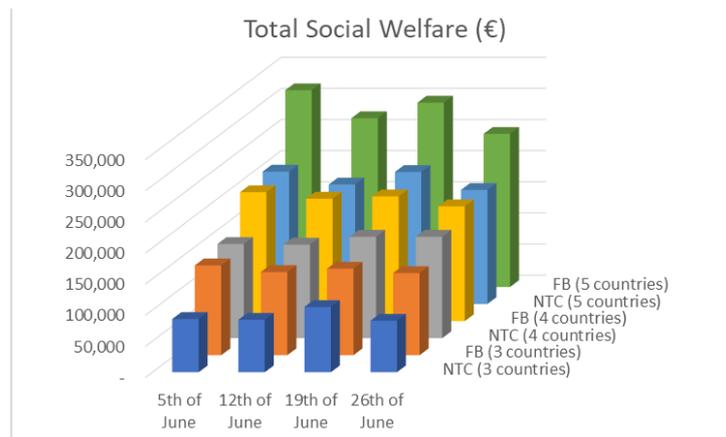


Figure 10. Total social welfare in euro via both approaches.

Finally, to give an overall view of the coordinated capacity calculation on cross-borders via market coupling procedure in the SEE region, a total performance index is introduced. The total performance index is defined in Equations (4) and (5) and gives a quick assessment of the effectiveness and performance of the NTC and FB approach, as these functionalities are tested in the frame of CROSSBOW ROC. This index is given in percentage (%) and is obtained by combining the two basic indexes of SW (%) and PC (%). The concept for TP (%) is a simple and prompt total evaluation of the NTC or FB method in every test case scenario. Thus, as the SW index increases and the PC index decreases, the TP index has a significant increase and the method examined is presented to be more effective in general terms. In Figures 11 and 12, the TP index is depicted in a graphical way for both NTC and FB approach, respectively.

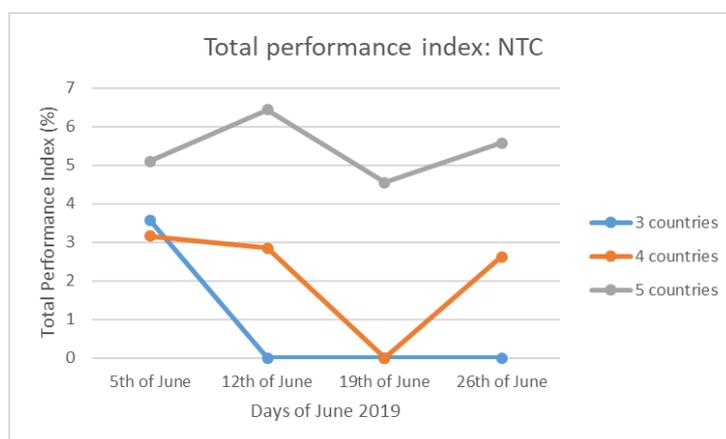
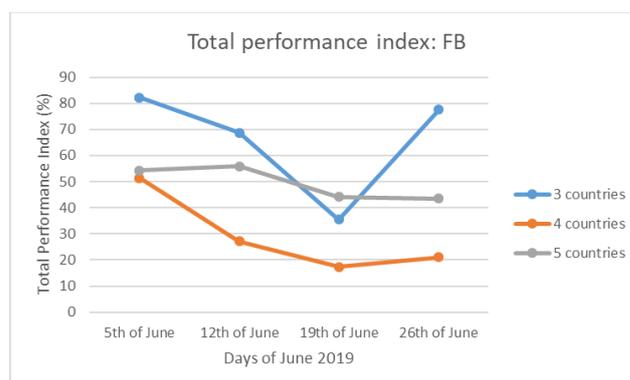


Figure 11. Total performance index calculated for NTC method.



**Figure 12.** Total performance index calculated for FB method.

#### 4. Conclusions

The main objective of this paper is the optimization of capacity calculation for cross-border electricity trade via market coupling, based on TSOs' regional coordination. In this frame, the H2020 CROSSBOW project has proposed and demonstrated its ROC product. Firstly, a historical context from RSCs to ROCs and the contemporary and future RCCs were presented, as retrieved by EU and ENTSO-E regulation and directives. In 2016, the CROSSBOW project proposed an ROC that encompasses a wide range of functionalities. The CROSSBOW ROC functionalities were presented and analyzed. Our primary focus is on cross-border capacity calculation via electricity market coupling. Specifically, the NTC and the FB approach are tested and validated in the SEE region for different network and time conditions, while the relevant results are illustrated via three KPIs.

In the NTC method, TSOs themselves calculate the capacity values based on forecasts and historical data, while under the FB market coupling, the market decides how transmission capacity is allocated over market parties. Thus, more capacity and more trading opportunities are offered to the market. Our tests verify the theoretical benefits that the FB approach brings to the cross-border trading. Firstly, the FB approach leads to better trading opportunities and better utilization of the interconnection lines. Secondly, the total social welfare is increased, and finally, the internal energy prices decrease due to the cross-border trading. Those results guarantee the effectiveness of the FB method in the SEE region.

In all scenarios tested for the SEE region, the FB method was assessed to be superior to the NTC one, while, as a general conclusion, the two methods have higher performance as more markets are coupled, as expected. Therefore, we can claim that the FB method will benefit the cross-border trading in SEE region and foster regional coordination by creating better trading opportunities. In view of this, ROC acts as a facilitator and ensures the safe and reliable operation of the network while maximizing the monetary benefits of the participants in this specific market zone.

As future work, the authors will extend the analysis to more and/or different countries and various periods. More CBs from the considered countries will be included. Another option for the authors is to extend the test cases incorporating and investigating more functionalities of ROC/RCCs.

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### Abbreviations

CROSSBOW	CROSS BOrder management of variable renewable energies and storage units enabling a transnational Wholesale market
RES	Renewable energy resources
SEE	Southeastern Europe
ROC	Regional operation center
ATC	Available transfer capacity
FB	Flow-based
KPI	Key performance indicator
RSC	Regional security coordinator
RSCI	Regional Security Coordination Initiative
TSO	Transmission system operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
IEM	Internal electricity market
CEP	Clean energy package
CACM	Congestion allocation congestion management
SOGL	System operation guideline
aFRR	Automatic frequency reserve replacement
mFRRRAM	Manual frequency reserve replacement Remaining available margin
RCC	Regional coordination center
SW	Social welfare
MCC	Market coupling capacity
PC	Price convergence
CB	Critical branch
CNE	Critical element network
CO	Critical outage
PTDF	Power transmission distribution factor
SCC	Security coordination center

### Appendix A

**Table A1.** Total social welfare for a typical hour of a typical day.

Scenario	Social Welfare (EUR)			
	5 June	12 June	19 June	26 June
Uncoupled markets (3 countries)	69,262	74,690	96,735	71,523
NTC (3 countries)	85,581	84,277	104,851	82,792
Flow-based (3 countries)	144,395	133,706	139,063	132,044
Uncoupled markets (4 countries)	125,302	132,998	146,817	118,020
NTC (4 countries)	151,449	150,408	162,944	162,944
Flow-based (4 countries)	207,145	196,706	200,410	184,493
Uncoupled markets (5 countries)	169,622	160,994	179,568	150,005
NTC (5 countries)	212,820	192,114	212,268	183,383
Flow-based (5 countries)	316,188	271,282	296,293	246,063

**Table A2.** Indexes for 5th of June.

Scenario	Social Welfare Index (%)	Market Coupling Capacities Index (MW)	Price Convergence Index (EUR/MWh)
NTC(3 countries)	23.6	1600.0	28
FB (3 countries)	108.5	7508.7	8
NTC(4 countries)	20.9	3048.0	28
FB (4 countries)	65.3	14,104.1	7
NTC(5 countries)	25.5	4064.0	28
FB (5 countries)	86.4	21,422.8	13

**Table A3.** Indexes for 12th of June.

Scenario	Social Welfare Index (%)	Market Coupling Capacities Index (MW)	Price Convergence Index (EUR/MWh)
NTC(3 countries)	12.8	1584.0	23
FB (3 countries)	79.0	6163.2	3
NTC(4 countries)	13.1	2960.0	18
FB (4 countries)	47.9	12,996.2	10
NTC(5 countries)	19.3	3754.0	18
FB (5 countries)	68.5	21,039.0	5

**Table A4.** Indexes for 19th of June.

Scenario	Social Welfare Index (%)	Market Coupling Capacities Index (MW)	Price Convergence Index (EUR/MWh)
NTC(3 countries)	8.4	1668.0	21
FB (3 countries)	43.8	7778.3	4
NTC(4 countries)	11.0	3090.0	21
FB (4 countries)	36.5	14,563.3	11
NTC(5 countries)	18.2	3927.0	21
FB (5 countries)	65.0	22,086.1	9

**Table A5.** Indexes for 26th of June.

Scenario	Social Welfare Index (%)	Market Coupling Capacities Index (MW)	Price Convergence Index (EUR/MWh)
NTC(3 countries)	15.8	1660.0	24
FB (3 countries)	84.6	7751.4	2
NTC(4 countries)	21.0	3324.0	21
FB (4 countries)	56.3	14,531.9	15
NTC(5 countries)	22.3	4664.0	21
FB (5 countries)	64.1	22,076.1	9

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