

# Cross-Border Participation in EU Resource Adequacy Mechanisms: Understanding the Contribution of Foreign Resources in Regional Markets

Geovanny Marulanda<sup>1,a</sup>, Antonio Bello<sup>1,b</sup>, Pablo Rodilla<sup>1,c</sup>,  
Paolo Mastropietro<sup>1,d</sup>, Javier Reneses<sup>2,e</sup>, Laurens De Vries<sup>3,f\*</sup>

## Abstract

Capacity Remuneration Mechanisms (CRMs) in the European Union (EU) are designed to ensure the adequacy of electricity supply by providing economic incentives for power generation capacity. While CRMs have been widely implemented at the national level, cross-border participation remains a challenge due to regulatory disparities and the absence of standardized approaches for determining the firm capacity of foreign resources. This paper proposes a generalized methodology for understanding the contribution of foreign market agents and eventually for computing de-rating factors for cross-border resources in CRMs, ensuring a level playing field between domestic and foreign capacity providers. The proposed framework builds on first principles, extending regulatory and economic analysis by integrating interconnection constraints and market price caps. Although the current EU market design applies a single harmonized price cap across all bidding zones, the paper adopts an intentionally asymmetric cap as a theoretical abstraction that isolates the role of price signals in cross-border scarcity situations. Through stylized case studies, this paper evaluates the effects of interconnection capacity, resource availability uncertainty, and market price caps on de-rating factors. The results indicate that disparities in the definition of the maximum price between interconnected markets and interconnection congestions significantly influence the

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<sup>\*1</sup> Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Calle del Rey Francisco, 4, 28008, Madrid, Spain

<sup>2</sup> Simulart Energy, Foronda, 6, 28034 Madrid, Spain

<sup>3</sup> Delft University of Technology, Faculty of Technology, Policy, and Management, Delft, 2600 GA, The Netherlands

<sup>a</sup> gmarulanda@comillas.edu (Corresponding author)

<sup>b</sup> abello@comillas.edu

<sup>c</sup> prodilla@comillas.edu

<sup>d</sup> pmastropietro@comillas.edu

<sup>e</sup> javier.reneses@simulart.es

<sup>f</sup> l.j.deVries@tudelft.nl

firm capacity recognized to cross-border resources. In addition, the results show that resource complementarity, while beneficial for overall system reliability, may paradoxically reduce the incentives for cross-border CRM participation.

**Keywords:** Capacity Remuneration Mechanisms; Cross-border Mechanisms; De-rating factors; Firm capacity; Resource adequacy

## 1 Introduction

In the EU, Capacity Remuneration Mechanisms (CRMs) are regulatory instruments that countries can employ to guarantee the reliability of their electricity supply over the medium and long term. They achieve this by offering additional remuneration to capacity resources (generation units, energy storage, and demand-side response) for being available when most needed [1]. Conversely, these resources can face penalties if they fail to deliver the contracted capacity [2]. Since the adoption of Regulation (EU) 2024/1747, CRMs are no longer viewed merely as measures of last resort [3]. Instead, they are integrated into a structured framework for ensuring resource adequacy, within which CRMs must be carefully designed to address the specific adequacy issue identified and remain time-limited, with a maximum duration of ten years [1], [3].

In the EU’s CRMs, the expected system reliability is calculated through resource adequacy assessments. These are based on the latest forecasts on supply-demand scenarios, considering the availability of renewable energy sources, demand side flexibility, reserves and storage, and cross-border infrastructure in times of system stress [4], [5]. The methodology cover all Member States. Two probabilistic resource adequacy metrics are used: Expected Energy not Served (EENS) and Loss of Load Expectation (LOLE) [4], which are evaluated through Montecarlo simulations. Other metrics have been proposed in the literature considering peak demand, capacity installed, desired reserve margin, and the least favorable scenario [6]. By using proper resource adequacy metrics, regulators and market participants can better assess the investments needed to maintain the security of the electricity supply.

CRM design includes firm capacity calculations to determine how much various resources will contribute to meeting adequacy requirements. These calculations estimate the resource’s availability during the expected system stress events, commonly expressing it as de-rating factors. De-rating factors account for potential unavailability due to maintenance, weather conditions, and equipment failures. The firm capacity is a fundamental part of the product traded (and therefore remunerated) within CRMs, and its mean to integrate diverse technologies in a single mechanism. This inclusive approach allows both conventional and intermittent generation, as well as storage and demand resources to participate in CRMs [6]. However, there remains a lack of consensus about

how to calculate the firm capacity (and the de-rating factors) of cross-border resources in CRMs [2], which is crucial to ensure a level playing field for all resources.

Cross-border participation enables the utilization of resources from neighboring regions or countries within local CRMs, leading to both reliability and economic benefits. In addition, cross-border participation can improve competition and allow for a more diverse mix of generation sources. Despite these advantages, cross-border participation in CRMs is not commonly observed in practice [1]. There is a recognized need for harmonizing rules across various CRMs for quantifying capacity supplied to or received from neighboring markets to promote and facilitate greater cross-border participation. Moreover, there are concerns regarding calculating the technical equivalence between foreign and local capacity resources to guarantee a transparent and competitive process [2]. In this regard, the literature lacks methodologies for allocating firm supply in a multi-area context. This paper proposes an approach to fill this gap, delving into the main determinants of the firm capacity of resources in a regional context involving cross-border participation, and examining how they affect firm capacity in ways that are not always intuitive.

The remainder of this paper is structured as follows: Section 2 reviews different CRM experiences in the EU and relevant academic literature. Section 3 introduces the proposed methodology for computing the firm supply of cross-border resources. Section 4 provides a qualitative analysis to illustrate the methodology and identify the key determinants influencing cross-border resource contributions. Section 5 presents numerical examples to validate the proposed methodology. Finally, Section 6 concludes the paper by summarizing the main findings and their implications.

## 2 Literature Review

### 2.1 Participation in cross-border CRMs in the EU

Cross-border participation in CRMs within the EU is regulated by Regulation (EU) 2019/943 [1], with the technical specifications outlined by the EU Agency for the Cooperation of Energy Regulators (ACER) in 2020 [7]. Member States are generally required to ensure that foreign capacity providers with equivalent performance to domestic resources have equal opportunities to participate in their mechanisms. Additionally, they must allow resources within their territories to participate in the CRMs of other Member States. Specifically, direct cross-border participation in CRMs enabled by physical interconnections between countries requires an agreement between the involved Member States' transmission system operators (TSOs) [2]. Furthermore, TSOs are responsible for determining the extent of cross-border participation in their national CRM

and assessing the expected contributions that foreign capacity could provide during times of system stress [1].

While the current regulations allow foreign capacity providers to be located in any part of the interconnected EU network, Member States have the authority to decide which specific neighbouring power systems are eligible to participate in their CRM, as long as they include at least those with a direct interconnection with the Member State implementing the CRM. Most Member States have decided to implement different methodologies for participating foreign resources in the competitive auctions of the CRMs. Some characteristics of these mechanisms, as presented in [2], are summarized below:

- **Poland:** Poland allows the direct participation of foreign capacity resources in its CRM. Unlike other Member States that rely on national assessments, Poland is the only one that uses the European Resource Adequacy Assessment (ERAA) to allow cross-border participation. The eligibility criteria and obligations within the mechanism are identical for foreign and domestic resources. Still, one clearing price for the national bidding zone and one for each participating foreign zone must be determined. In addition, it has TSOs' agreements in place. The rules to participate in the Polish CRM can be consulted in [8].
- **Italy:** Italy has implemented a simplified approach for direct cross-border participation. In this approach, the obligations of foreign participants in the CRM have been reduced, mainly because the Italian authorities consider foreign resources incapable of providing the same technical performance as domestic resources, as discussed in [2]. Unlike Poland, the limits for cross-border participation in the national CRMs are based on historical flows rather than the ERAA methodology, and no TSOs agreements are currently in place.
- **Belgium:** Belgium is expected to allow the direct participation of both additional and existing foreign capacities from winter 2025/2026 [2], [9]. Indirect foreign capacity providers can only sign single-year contracts. This allowance is due to the nature of cross-border participation, which varies annually and is not precisely known in advance for each delivery period and border [9]. Although there are no TSOs agreements, they are expected to be in place early. Along with Poland, eligibility criteria and obligations into the mechanism are the same for both foreign and domestic resources. However, Belgium uses a national assessment instead of the ERAA methodology.
- **France:** France has already established the rules for direct cross-border participation, allowing resources and interconnectors to participate directly in the domestic CRM auctions. Although regulations exist for the direct involvement of foreign capacity, they remain unimplemented, and

only participation via interconnectors is allowed. Specifically, it is anticipated that foreign capacities will come into operation within the new CRM either by the end of 2026 or in the early months of 2027.

- **Ireland:** Ireland has begun formulating detailed regulations to facilitate direct cross-border participation, anticipating the expected Celtic interconnector with France by 2026.

## 2.2 Academic literature related to CRMs in a regional context and the effects of cross-border participation

Several authors have examined CRMs and their cross-border effects using game-theoretical models [10], [11], [12]. Tasios et al. [10] employed a modified version of the PRIMES model to assess the capacity remuneration needed to cover investment costs in open-cycle plants in the EU electricity market. The study concluded that an energy-only market is unlikely to secure the necessary investments in Combined Cycle Gas Turbine (CCGT) plants for balancing and backing up renewable energy sources unless market conditions become highly concentrated. Additionally, the authors found that asymmetric remuneration distorts investments and leads to free-riding situations. Meyer et al., Hoschle et al., and Lambin et al. [11], [12], [13], highlighted the inefficiencies resulting from uncoordinated CRM designs, which can negatively impact market welfare and underscore the need for cross-border coordination. Meyer et al. [11] analyzed Strategic Reserves (SRs) and Reliability Options (ROs), showing that ROs increase competition and lower electricity prices, while SRs reduce overall market efficiency. Hoschle et al. [12] expanded this analysis by incorporating operational and investment decisions, demonstrating that harmonizing CRMs across borders benefits the system. However, the effectiveness would depend on applying appropriate de-rating methodologies for interconnections. Lambin et al. [13] further explored the implications of domestic support schemes for generation capacity, examining energy-only markets, capacity markets, and SRs. They found that for capacity markets to function effectively, transmission capacity must be limited, or TSOs should be able to reduce export capacity, contradicting EU electricity market principles. Moreover, the unilateral adoption of capacity markets can reduce operational capacity in neighboring markets, prompting them to introduce their own capacity markets.

Recently, Menegatti and Meeus [14] developed an equilibrium model to analyze a two-zone electricity system, assessing the impact of “explicit” and “implicit” cross-border participation in national capacity markets. Their findings show that cross-border participation only partially reduces the externalities of a national capacity market on neighboring consumers, generators, and interconnections in systems without a CRM. Furthermore, both participation models suggest no clear advantage in choosing one over the other. Notably, results show that national CRMs can fail to ensure the security of supply due to their cross-border effects. Based on these insights, the authors advocate for a transition

from national capacity mechanisms to a European-wide adequacy framework and suggest shifting from explicit to implicit cross-border participation, as it simplifies implementation without compromising effectiveness.

In contrast to the above references, in [15], [16], [17], agent-based models have been developed to study the cross-border effects of CRMs. Similar to [11] and [13], Bhagwat et al. [15] focus on the impact of SRs and capacity markets on supply security and economic efficiency. Results show that interconnections can negatively impact SRs, whereas capacity markets remain largely effective. Also, it is shown that SRs in one zone could spill over benefits to interconnected zones. However, interconnected zones with energy-only markets can experience a reduction in investment and an increase in their import dependency. In [16], the impacts of market designs adopted by larger neighboring countries on smaller adjacent markets are analyzed, using the Swiss electricity market as a study case. The model includes both energy-only markets and CRMs. The findings indicate that while CRMs might lead to increased installed capacities in larger countries, they also tend to increase the reliance of smaller countries on imports and their power dependency. In Fraunholz et al. [17], different risk preferences of agents on capacity expansion planning are evaluated using a case study of the European electricity market. Results show that risk aversion could reduce investments and resource adequacy and increase prices. Likewise, they show that the negative effects of risk-averse behavior are lower in markets under CRMs than in energy-only markets.

Bucksteeg et al. [18] and Astier et al. [19] have introduced models incorporating probabilistic and optimization elements. In Bucksteeg et al. [18], the effects of different grades of coordination and geographical coverage of the capacity market are analyzed. The approach involves a probabilistic method for determining capacity requirements, followed by applying an optimization model to simulate both short- and long-term electricity market scenarios. The results reveal that uncoordinated actions may result in inefficiencies and compromised supply security due to an unfavorable allocation of generation capacity. In Astier et al. [19], the proposed model minimizes the generation expansion cost in three possible scenarios faced by neighboring countries: First, one country assumes that imports from another country are always available and the import capacity is not constrained. Second, one country expects that other countries will only offer to export electricity if they are not experiencing shortages. Third, one country prioritizes exports to other countries, even if it is necessary to produce shortages in its own country. Results show that defining reliability standards without considering interconnections can still be used for interconnected systems. Differing from the approaches in [18] and [19], the model proposed in [20] introduces a probabilistic methodology centered on the Loss of Load Probability (LOLP). This approach is utilized to investigate the influence of interconnection capacity on generation adequacy within regional power systems, employing a two-zone model for the analysis. Authors show that expanding transmission capacity has a limit to improving adequacy and that increasing the capacity

above this limit does not produce additional benefits.

Cepeda [21], and Hickey et al. [22] offer different approaches to those mentioned above. In [21], the effects of including cross-border generators and interconnectors in national CRMs and their impacts on social welfare, investment incentives, and market efficiency are explored. For this, a system-dynamics model is proposed, allowing the participation of interconnectors in the CRM, the price formation, and the investment decision-making. The study reveals that excluding cross-border participation in CRMs can lead to substantial social welfare losses and negatively affect market efficiency. These losses stem from the risks associated with over- or under-procurement of capacity. In contrast, [22] proposes a cash-flow model to analyze the capacity remuneration needed across European member states to mitigate the “missing money” problem. The model is applied to assess investments in gas-fired power plants by 2030. The authors highlight that future investments will depend on the availability of capacity payments. Moreover, they suggest that implementing asymmetric remuneration schemes across European member states could alleviate the missing money problem.

Closer to the approach proposed in this paper, [23] and [24] have developed optimization approaches to calculate the contribution of different resources to improve resource adequacy in a regional market. Hagspiel et al. [23] develop a model to assess the contribution of transmission capacities and variable renewable resources on the amount and the optimal allocation of firm capacity. The proposed methodology involves calculating the contribution of the new resources to the reliability metrics, performing an iterative procedure in which each technology is deactivated, and computing the changes in Equivalent Firm Capacity (EFC). Results show that regional cooperation is highly beneficial, and reliability targets could strongly impact allocating new capacity and its contributions to reliability metrics. Based on the EFC methodology by Hagspiel et al., Peter et al. propose in [24] to determine the capacity value of wind power endogenously into the optimization model. For this, an iterative approach is proposed to model the non-linear relationship between the contributions of variable renewable energy to the security of supply on installed capacity and its spatial distribution considering cross-border cooperation. The results show that the contributions of wind power to the security of supply could be substantial for the EU (above 10% of the expected energy not served) and heterogeneous across regions and years. However, the contributions are affected by varying wind conditions, resource correlation among areas, total installed capacities, and interconnections.

### 3 Methodology

CRMs provide additional incentives on top of the energy market price signals to encourage new investments and also an efficient operation of the different resources (generation, flexible demand, and storage) during system stress events.

These additional incentives are meant to ensure that a certain reliability standard is met (e.g., EENS lower than 0.001% of the annual demand, or LOLE, lower than 3 hours by year [2]). The CRM should ideally remunerate resources regardless of their location, as long as they can help achieve the reliability standard in the system implementing the mechanism. Moreover, in a regional context, national CRM should allow for the participation not only of domestic generation resources but also of those installed (or that could potentially be installed) in other interconnected power systems. This is the solution that maximizes the overall economic efficiency in the regional market. To achieve this end, a necessary step is for CRMs to adequately define the methodology for determining the firm capacity of the different resources, both domestic and cross-border ones.

### 3.1 Computing the firm supply of cross-border resources based on first principles

In this paper, the firm supply of resources is obtained by extending the methodology presented in [6] to a regional context where each country defines different reliability targets with potentially different reliability metrics. The reasoning follows the traditional regulatory analysis methodology outlined in [25] and can be summarized as follows:

- First, a benchmark optimization problem corresponding to the ideal regional central planner's problem is formulated and analytically solved. The system is planned to maximize social welfare (accounting for the demand utility and the investment and operational generation costs in all the regions). In this central planner problem, a reliability standard is set in each individual domestic electricity system.
- Then, the equivalent profit-maximizing optimization problem for individual agents is formulated and analytically solved within the context of a perfectly competitive regional market. In this framework, agents respond not only to the spot market signal but also to an additional incentive introduced through the CRM that seeks to ensure meeting the reliability standard, thus providing a further economic signal to the firm supply assigned to each resource.
- Finally, we compare the optimality conditions of the two previous problems to derive the optimal price signal to be given to the firm supply of the different types of generation resources to efficiently meet the reliability objective.

The result of such a comparison leads to the conclusion that the CRM-related remuneration, and therefore the firm capacity, should be proportional to the following expression (the demonstration is provided in Section 8):

$$\Phi_i^j = \frac{\partial RM_j}{\partial K_i} \quad (1)$$

where  $\Phi_i^j$  is the marginal contribution of resource  $i$  to the reliability of market  $j$  where a reliability standard has been set. This method implements a CRM and provides additional remuneration to incentivize investments that help meet the reliability standard. Likewise, subindex  $i$  refers to the generation asset under study,  $K_i$  represents the installed capacity of resource  $i$  (expressed in MW), and  $RM_j$  represents the reliability metric used to set the reliability standard by the regulator (or system operator) in the system  $j$ . In other words, in the context of a CRM implemented in system  $j$ , the optimal incentive to be provided to resource  $i$ , located in any interconnected system, should be proportional to the marginal contribution of the resource to the reliability metric established in system  $j$ . This marginal contribution is driven by the characteristics of the resource (availability, operational constraints, correlation with stress events in the CRM-system), the characteristics of the interconnected systems (generation technologies, demand profile, and consequently correlation of stress events), on the network (whether it is available or not and whether it is congested or not, especially at times of system stress in one of the interconnected systems) and also on the reliability metric defined by the regulator of the CRM-system to set the reliability standard.

### 3.2 Expressing the marginal contribution in MW

We have stated that the firm supply should be proportional to the value provided by expression (1), whose units are those of the reliability metric divided by MW. However, it is common practice to define this firm capacity or firm supply in MW. Obtaining such a value involves two further steps:

- First, define a reference asset at the node where the CRM is implemented (e.g., a 1-MW ideal flexible generator with 100% availability installed in the CRM system).
- Then, assign any capacity resource to this 1-MW reference asset (which is somehow arbitrary). For example, 1-MW of firm capacity could be assigned to a 1-MW ideal generator.

Once we have defined such a reference asset, we can compare the value provided by expression (1) for the ideal generator located in the CRM system and for any other asset located in the national or any interconnected system and assign the number of MW of firm capacity accordingly. That is, if (1) results in 0.80 for the 1-MW ideal generator and 0.40 for 1 MW of a given generating asset in the interconnected system, then the firm capacity of the latter asset would be 0.5 MW. The same approach can be used to define de-rating factors. The de-rating factor is essentially a coefficient that, when multiplied by the installed capacity of a resource, such as a generation unit, leads to the firm capacity of that resource. In our previous example, the de-rating factor would therefore be 0.5 or 50%. Notice that this approach also allows for defining a standard product regardless of the reliability metric.

### 3.3 Simulation models for reliability studies

In order to compute this marginal contribution, the reliability metric needs to be necessarily evaluated through a detailed simulation model that processes the key fundamental variables reflecting operational dynamics of the power system over the planned period [6]. In such a framework, uncertainty needs to play a key role, either by means of Monte Carlo scenario simulation (the approach used in this paper) or by means of a scenario tree and stochastic programming. The reliability metric should be tied to a statistical parameter (like the expected value or a percentile) in such a way that it synthesizes the outcomes from all the various projected scenarios. Using this detailed simulation model, the three steps in the general methodology to compute the firm supply of cross-border resources can be summarized as follows:

- **Establish the baseline scenarios and determine the value of the reliability metric:** In this stage, the planning simulation model is solved for the scenarios set as the baseline. These scenarios serve as the reference point from which the marginal contributions of individual resources to the  $RM_j$  will be calculated. For example, if 100 scenarios (represented by means of Monte Carlo or by a scenario tree) are set as the baseline scenarios that better capture the future evolution of the mix, we compute ex-post the  $RM_j$  (e.g. the EENS) resulting from these 100 scenarios. For the analysis in this paper, a medium-term generation planning model considering various technical constraints, has been proposed and detailed in the Section 9.
- **Increase marginally ( $\Delta K$  relative to the baseline) one by one the installed capacity for the resources whose firm capacity is to be evaluated and the reference assets:** The planning problem is then solved again for each incremented capacity, and the reliability metric is re-evaluated for all the scenarios (the 100 mentioned before). The change in the reliability metric due to the change in the capacity of the resource  $i$ ,  $\Delta RM_j^i$ , is calculated by comparing the reliability metrics obtained in this stage with those from the baseline for each market. This step linearizes the derivative of equation (1) around the installed capacity of the resources whose firm capacity is to be evaluated, using first the approximation  $\partial K_i \approx \Delta K$  and then  $\partial RM_j^i \approx \Delta RM_j^i$ . This process is repeated for each market offering a CRM to determine the marginal contribution of each reference asset to its reliability metric, using the approximation  $\partial RM_j^* \approx \Delta RM_j^*$ , where the superscript “\*” denotes the reference asset.
- **Comparison with the reference asset:** In this final stage, the marginal contributions of each cross-border resource are compared with those of the reference assets in the CRM market. The de-rating factor is the ratio between these contributions, as explained in [6]. Resources whose marginal contributions closely match those of the reference assets will have de-rating factors near one, while those with much lower contributions will have de-rating factors closer to zero. Since the same step  $\Delta K$  is used for both new

resources and reference assets, the de-rating factor for each unit in a given market can be calculated as:

$$df_i^j = \frac{\Delta RM_j^i}{\Delta RM_j^*} \quad (2)$$

## 4 Qualitative analysis of the firm supply determinants in a regional setting

Before presenting numerical examples, this section explores the main factors influencing the firm supply of cross-border resources, or, in other words, the variables that affect the ability of resources located in a neighboring country to contribute marginally to the reliability metric of a system implementing a CRM. First, we propose a stylized case study to understand the implications of expression (2). First, we define a basic setting representing two neighboring systems in the EU context and then analyze four relevant cases that illustrate when and how cross-border resources contribute to system adequacy, both in overall and marginal terms. Finally, we identify the key determinants shaping their firm supply, based on the insights gained from these cases.

### 4.1 Stylized study case: setting and basic features

In the following, the discussion will be based on two countries, one where a CRM is implemented (the CRM-system in the following) and a neighboring system (the N-system). They are interconnected by a fully available transmission line, and generators in the N-system are allowed to take part in the CRM of the CRM-system. The CRM consists of incentivizing resources (domestic and cross-border) in proportion to their firm supply, calculated on the basis of (1). This is the simplest form of CRM, but it includes the main element of interest for our analysis (an incentive proportional to the firm supply). We avoid considering additional design elements of the CRM which are not relevant to this analysis. The CRM-system, defines a reliability standard based on an expected unserved energy reliability metric (which is the most common practice worldwide in electricity markets). This reliability metric will be denoted as RM. In this two-country context, two key features are worth highlighting, as they will be crucial in the analysis presented in the next sections:

- **Feature 1:** It is assumed that both short-term markets are integrated in such a way that the welfare is maximized for the whole system. As a consequence, cross-border flows are determined by short-term spot market prices. If there is a price difference between the two systems connected by the interconnector, electricity flows from the lower-priced system to the higher-priced one. When prices are equal at both ends, the interconnector is not congested, allowing free flow in either direction<sup>1</sup>. The two-country

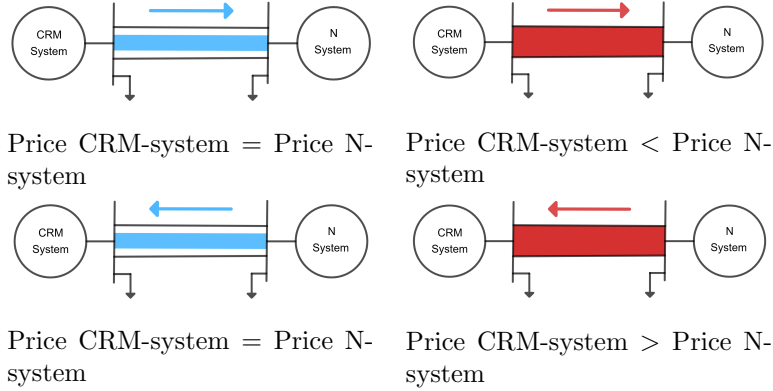
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<sup>1</sup>This assumption holds only if grid losses are not accounted for, which will be the case in our analysis.

framework is illustrated in the figures below, in which a schematic representation of some cases of interest is provided:

- Two cases where the interconnector is not congested (shown on the left, with the interconnector in blue), one per each possible direction of the resulting flow.
- Two cases where the interconnector is congested (shown on the right, with the interconnector in solid red), one per possible direction of the resulting flow.

The blue and red arrows indicate the direction of the flow in each scenario, which, as depicted, depends on the prices at both ends.



Two-country framework in the different cases

- **Feature 2:** We will assume that each system has implemented a maximum national energy price<sup>2</sup>. The maximum prices will be referred to as  $P_{max}^{CRM-system}$  and  $P_{max}^{N-System}$ , respectively. These maximum prices occur in the system whenever the system is experiencing a shortage. We will assume that both national maximums are above the variable cost of any plant in either system.

As a result of the previous conditions, we can also assume that if one and only one of the systems reaches the maximum price (there is a scarcity), then the interconnector will always be congested in the direction of the system where

<sup>2</sup>Regulators more often than not establish these maximum energy prices in electricity markets for several critical reasons: to protect consumers from sudden price spikes, to maintain market stability or simply to reflect consumers' willingness to pay. These maximum prices can be dynamic. For example, in Europe, the coupled spot electricity markets are equipped with an automatic mechanism for adjusting the maximum price limit during periods of exceptionally high prices. In this respect, the European Agency for the Cooperation of Energy Regulators (ACER) approved in 2023 some changes to the methodologies used for these adjustments. The last revised methodologies result in a more gradual increase in the price limits of the day-ahead and intraday markets compared to the previous rules.

the maximum price has been reached. However, whenever there are coincident scarcities in both interconnected systems, the direction of the flow will depend on where the maximum price is higher. These are key ideas that will be used in the next section. It is important to notice that this analysis is based on a theoretical abstraction. In the actual EU electricity market design, maximum price limits are harmonized, with a single cap applying uniformly across all bidding zones within each market segment (e.g., day-ahead, intraday). Nevertheless, the assumption of asymmetric maximum prices is useful for analytically isolating the role of price signals in cross-border scarcity situations.

## 4.2 Case analysis: 4 types of settings that help to understand the marginal and overall contribution of cross-border resources

The analysis focuses on four representative types of hourly settings in which the CRM system experiences scarcity. These settings capture the different conditions under which resources contribute to system adequacy and determine their firm supply. Any more comprehensive assessment, covering longer or annual horizons, can be interpreted as a combination of these four types hours. The CRM-system price in these periods will always be  $P_{max}^{CRM-system}$ . In this scenario, and provided the aforementioned conditions, the flow direction and whether or not the interconnector is congested will be determined exclusively by whether the price in the N-system is higher, lower, or equal to the one in the CRM-system. Thus, there are three potential situations (indeed four, as we shall see) for those hours of scarcity in the CRM-system:

### 4.2.1 Case 1: The price in the CRM-system is higher than the price in the N-system



Figure 1: Case 1.  $P_{max}^{CRM-system} > P_{max}^{N-System}$

In this scenario, as explained previously, the interconnector is necessarily always congested in the direction of the CRM-system, no matter whether or not there is scarcity in the N-system. Consequently, any marginal increase in the installed capacity of a resource in the N-system will not improve the RM in the CRM-system. This is because the interconnector does not permit the additional energy to reach the CRM-system. Note that during these hours, there is an overall positive contribution from the N-system to the RM of the

CRM-system, since the RM would worsen if the interconnection did not exist. However, it should also be noted that there is no marginal contribution from any resource installed in the N-system. Therefore, the firm capacity of any resource in the N-system relative to these hours will be zero, as will be the remuneration provided by the CRM-system to this resource.

#### 4.2.2 Case 2: The price in the CRM-system is lower than in the N-system



Figure 2: Case 2.  $P_{max}^{CRM-system} < P_{max}^{N-System}$

In this scenario, the interconnector is congested in the direction of the N-system. This can only happen if the N-system is suffering a scarcity and the  $P_{max}^{N-System}$  is higher than  $P_{max}^{CRM-system}$ . When this is the case, any marginal increase in the installed capacity of any resource in the N-system will not improve the RM metric in the CRM-system because the economic flow does not allow the energy in the N-system to reach the CRM-system. Note that during these cases, there is a negative overall contribution of the N-system to the RM metric of the CRM-system. If the interconnector did not exist, the RM of the CRM-system would improve. Regarding the firm supply computation, there can be no marginal contributions from resources installed in the N-system, and therefore, the firm capacity relative to these hours will be zero, as will the remuneration provided by the CRM-system to this resource.

#### 4.2.3 Case 3: The price in the CRM-system is equal to that of the N-system

In this case, the interconnector will not be congested. Here, the flow could sometimes go from the N-system to the CRM-system (which we will denote as case 3.1, see the figure 3). But the flow could also go in the opposite direction, as shown in figure 4 (that is, from the CRM-system to the N-system). We will denote this case as 3.2. In these types of hours, the overall and the marginal contribution of the N-system will depend on the allocation rule in the clearing algorithm. We further discuss this aspect in the following section. In case 3.1, the overall contribution will be positive, while in case 3.2, it will be negative, but the size will depend on the details of the algorithm clearing the market, since there are multiple dispatch solution leading to the same welfare. However, what matters in both cases is that there is a potential marginal contribution to the RM of the CRM-system for the resources installed in the N-system.

In case 3.1, adding one MW in the N-system could result in an increase in the flow through the interconnector (which is feasible since the interconnector is not congested) towards the CRM-system, alleviating its scarcity conditions. In Case 3.2, adding one MW in the N-system could also lead to a reduction in the import needs of the N-system, thus decreasing the flow through the interconnection and allowing more energy to remain in the CRM-system, consequently enhancing the RM. Based on the previous considerations, it is straightforward to derive the marginal contributions to the cross-border CRM depending on two key conditions: whether or not there are scarcity conditions also in the N-system and whether the maximum price is higher, lower, or equal in the N-system than in the CRM-system. The resulting combinations are evaluated next.

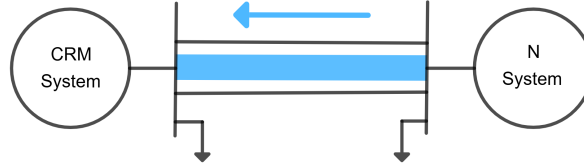


Figure 3: Case 3.1.  $P_{max}^{CRM-system} = P_{max}^{N-System}$  with flow from the N-system to the CRM-system

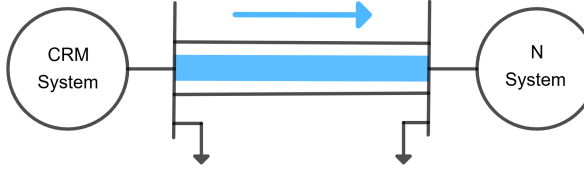


Figure 4: Case 3.2.  $P_{max}^{CRM-system} = P_{max}^{N-System}$  with flow from CRM-system to the N-system

### 4.3 The key determinants affecting the contributions of cross-border resources

Using the reasoning provided in section 4.1 and 4.2 and referring to the four cases identified in the last section, we can now analyze the two key determinants that shape the firm supply of cross-border resources: the maximum prices and the amount of hours with concurrent scarcities. This section begins by examining scenarios where maximum prices differ between the CRM-system and the N-system, illustrating their impact on resource contributions. Next, it explores the case where maximum prices are equal, addressing the need for a clear allocation rule during simultaneous scarcity conditions in both systems.

#### 4.3.1 Maximum prices

The maximum price levels in the CRM-system and the N-system play a critical role in determining the marginal contributions of cross-border resources. Three main cases can be distinguished depending on whether the maximum price is higher in the CRM-system, higher in the N-system, or equal in both.

##### **The maximum price is higher in the CRM-system**

When the maximum price is higher in the CRM-system, all hours during which the CRM-system experiences scarcity correspond to those observed in case 1. Consequently, the N-system makes a net positive contribution to the RM. However, there is no marginal contribution from any resource within the N-system because the interconnection is congested, and no additional contribution may take place, thus leading to a firm capacity equal to zero for any resource in the N-system. This situation may be perceived as the N-system contributing to the CRM-system without receiving any compensation.

##### **The maximum price is higher in the N-system**

A different situation arises when the maximum price is higher in the N-system. When the N-system operates under normal conditions (the maximum price in the N-system is higher than in the CRM-system, but it is not active since there are no scarcity conditions in the N-system), we again fall into case 1, where we have said that there is no marginal contribution from any resource in the N-system. However, when the N-system is supplying exactly its demand (and either exporting the surplus or importing some energy to ensure the national demand is supplied), both the CRM-system and the N-system will have equal prices (the maximum price in the CRM-system), thus we fall under cases 3.1 or 3.2. During these periods, resources in the N-system do make marginal contributions. However, when the N-system undergoes a scarcity event, its prices rise above the one in the CRM-system, placing us in case 2, where there is no possible marginal contribution from any resource in the N-system. Therefore, in this scenario, the cross-border resources will have firm capacity, and this value will depend on the weight that case 3.1 and case 3.2 hours represent over the total amount of hours where the CRM-system suffers a scarcity.

##### **The maximum price is the same in both the CRM-system and the N-system**

Finally, when both systems have the same maximum price, the contribution of N-system resources depends entirely on system conditions. If the N-system operates under normal conditions and the CRM-system suffers a scarcity, we fall again into case 1, where there is no marginal contribution from any resource in the N-system. If both the CRM-system and the N-system have equal prices ( $P_{max}^{CRM-system}$ ), we fall under Case 3.1 or 3.2. During these periods, resources

in the N-system do make marginal contributions. Ultimately, the frequency of occurrences of Case 3.1 or 3.2 will determine the amount of firm supply allocated to the resources. However, it must also be remarked that when the maximum prices are reached in both systems, meaning that both systems are suffering scarcity conditions, an allocation rule will be required for the clearing algorithm to define the dispatch of generation and demand in the two systems. A possible allocation rule could prioritize the supply of demand in the CRM-system, recognizing the CRM contracts signed by resources located in the N-system. Another allocation rule may consider an equal sharing of non-served energy among the two systems proportionally to the maximum demand. This topic has not been addressed in academic literature, but it is very relevant for CRM cross-border participation. Without a clear allocation rule, the risk is that system operators decide to stop the flow through the interconnection during concomitant scarcity conditions in the two systems.

#### 4.3.2 Concurrent scarcities

The discussion then shifts to the role of concurrent scarcities. In particular, there are two factors affecting to the number of hours of this type: the amount of interconnection capacity, highlighting its influence on congestion and the firm power contributions of neighboring resources, and the complementarity of demand and renewable production profiles, showing how staggered consumption and production patterns can enhance reliability metrics while reducing the firm capacity of cross-border resources.

When maximum prices are coordinated (equal) across both systems, the relationship between the frequency of concurrent scarcity events and the contribution of cross-border resources becomes more nuanced. As the number of coincident scarcity hours increases, the total contribution of the neighboring country to the CRM-system's reliability and the flow in the interconnector tends to decrease, since both areas are simultaneously constrained. However, during these periods, the marginal contribution of individual resources located in the N-system increases, as any additional unit of available capacity in those hours has a higher impact on mitigating scarcity conditions in the CRM-system. In other words, more concurrency means less total energy can be delivered across the border, but a higher value for each marginal MW that can respond in those critical moments.

As will be shown numerically in the next section, the allocation rule adopted during coincident scarcity situations becomes a decisive factor in determining whether cross-border resources are effectively recognized within the CRM. When maximum prices are harmonized across systems, the allocation rule defines the dispatch priority of available capacity and the direction of flows through the interconnector. If the rule guarantees that contracted resources in the neighboring system can deliver to the CRM-system even under scarcity in their own area, the recognized firm supply and de-rating factors increase substantially.

| Technology | Operational cost<br>[€/MWh] | Maximum power<br>[GW] | Minimum power<br>[GW] |
|------------|-----------------------------|-----------------------|-----------------------|
| Nuclear    | 2.2                         | 5                     | 4.5                   |
| Hydro      | -                           | 16.9                  | 5.63                  |
| Gas        | 4                           | 1.15                  | 0.38                  |
| CCGT       | 2.5                         | 26.25                 | 8.75                  |

Table 1: Main data of the test system

Conversely, if the rule prioritizes national adequacy and restricts exports during such periods, the cross-border contribution is almost nullified. Therefore, the allocation rule not only shapes the short-term flow patterns during scarcity events but also critically influences the long-term investment incentives for foreign participation in CRMs.

## 5 Results

### 5.1 A deterministic case example that illustrates the role of these three determinants

The proposed theoretical framework is first tested in a deterministic interconnected electricity market system with two areas as described in section 4.1. For the sake of simplicity, a single 24-hour deterministic scenario has been considered, where the peak demand in the CRM-system is 100 GW, the ENS is 100 MWh, and the interconnector capacity is higher than 2 GW. The marginal change is approximated with an increment of 1 MW, which is too small to significantly impact dispatch or system constraints. In this way, 1 MW can be considered sufficiently small to serve as a “marginal value” and ensure high accuracy in further analysis. Table 1 presents the relevant data for this test system, including the costs and the maximum and minimum aggregated production capacities for different technologies. Both CRM-system and N-system share similar characteristics, and the interconnection capacity between both markets is assumed to be 5 GW. In this first case study case, we evaluate the firm capacity of combined cycle power plants (CCGTs) installed in the N-system and participating in the cross-border CRM.

This case example analyses the two above-mentioned determinants: the effect of the maximum prices and the effect of concurrent scarcities on firm supply and overall reliability. Regarding the impact of the maximum price in each system on firm supply, two scenarios are simulated: A and B. In Scenario A, the maximum price in the CRM-system is lower than in the N-system, while in Scenario B, the maximum prices are equal in both systems. The third possible configuration, in which the maximum price in the CRM-system is higher

than in the N-system, is not simulated here, as it leads to case 1 conditions, where the interconnection is congested and no marginal contribution from the N-system can be registered. In both scenarios, cross-border de-rating factors are computed using both the general approach described in section 3.3, and also by accounting for the weight of the hours in which there is a marginal contribution (using the case analysis presented in section 4.2). Then, the study evaluates how concurrent scarcities affects firm supply. Two 24-hour wind power profiles have been simulated, as shown in Table 2. In profile 1, wind production is higher during the early hours and decreases throughout the day. In contrast, profile 2 exhibits the opposite pattern, with production increasing later in the day, making these profiles complementary. Based on these patterns, two scenarios were analyzed: low complementarity (both areas using profile 1) and high complementarity (CRM-system using profile 1, while the N-system uses profile 2). These profiles are intended as illustrative examples rather than realistic representations. Finally, for this case study, it is assumed that CCGT presents 100% of availability. This creates an “ideal” resource also on the N-system side, which is always dispatched when the maximum price is achieved in the CRM-system (or, what is the same, when non-served energy is registered in the CRM-system). However, unlike the “ideal” resource in the CRM-system, the contributions of this new resource are constrained by the interconnection capacity. This assumption helps simplify further analysis. Other scenarios are addressed in the more comprehensive case study presented in section 5.2.

| Profile | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1       | 5.02 | 4.95 | 4.94 | 4.98 | 4.97 | 4.80 | 4.60 | 4.41 | 3.83 | 3.66 | 3.03 | 2.68 | 2.34 | 2.05 | 2.02 | 1.86 | 1.76 | 1.63 | 1.57 | 1.26 | 1.05 | 0.99 | 0.76 | 0.55 |
| 2       | 0.55 | 0.76 | 0.99 | 1.05 | 1.26 | 1.57 | 1.63 | 1.76 | 1.86 | 2.02 | 2.05 | 2.34 | 2.68 | 3.03 | 3.66 | 3.83 | 4.41 | 4.60 | 4.80 | 4.97 | 4.98 | 4.94 | 4.95 | 5.02 |

Table 2: Wind power profile

### 5.1.1 Case 1A: The CRM-system maximum price is lower than the N-system maximum price

Figures 5 and 6 display the main results for the low and high complementarity scenarios (while the impact of the interconnection is analyzed in Case 1c), referred to as Scenarios 1 and 2, respectively. In both cases, the maximum price in the CRM-system is assumed to be lower than in the N-system. Both figures use continuous lines to illustrate the generation and demand in the two systems. The bars at the bottom of the figures illustrate key aspects to evaluate the cross-border contributions: ENS in each area (represented in red for CRM-system and orange for the N-system), interconnection congestion (in yellow), and the expected contribution of the N-system resources to the CRM-system reliability (in green). It is important to note that while the continuous lines depict the magnitudes of generation and demand, the height of the bars serves only to indicate the presence of ENS, congestion, and the “predicted” cross-border contributions in a given hour, not their magnitude. Notice also that the

peak demand has been deliberately set much higher than the system’s capacity (close to 100 GWh for the CRM-system) in this analysis to better highlight some scarcity conditions. In this way, this setup is not intended to reflect realistic conditions.

A marginal contribution from the resource located in the N-system to the scarcity conditions experienced in the CRM-system is possible only when the following conditions are met. First, ENS exists in the CRM-system in hours 7 to 9, 19 to 22, and 24. Second, the interconnector must be uncongested (all hours except 7, 9, 19, and 22). Third, the N-system should not experience ENS (all hours except 9). And fourth, the energy must flow from the N-system to the CRM-system (all hours except 9 and 10). Therefore, the hours when all conditions are met are 8, 20, 21, and 24 for Scenario 1 and 8 and 21 for Scenario 2. These specific hours are highlighted in green in Figures 1.2 and 1.3. Note that the key difference between the two scenarios lies in hours 20 and 24, where the N-system reaches its maximum generation capacity without fully utilizing the interconnecting capacity.

In this case study, with all this information, calculating the cross-border de-rating factors of a 100% available cross-border unit is straightforward. Notice, on the one hand, that the marginal contribution of the reference asset is 1 MWh in each hour the CRM-system experiences ENS because it is always dispatched. In Scenario 1, for instance, the reference asset would contribute 8 MWh to the CRM-system reliability. Similarly, the new resource in the N-system, acting as an “ideal” unit, contributes 1 MWh by each hour the CRM-system has ENS, and the interconnector is uncongested for the same scenario. This results in a contribution of 4 MWh to the cross-border CRM and a de-rating factor equal to 50% for Scenario 1. A similar analysis shows that the reference asset contributes 8 MWh to the cross-border CRM, while the new resource in the N-system contributes 2 MWh. This results in a de-rating factor equal to 25% in Scenario 2.

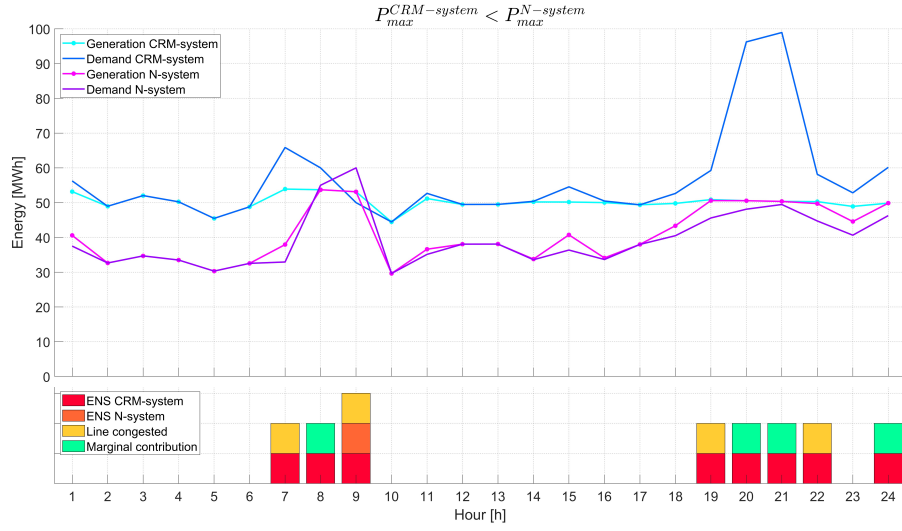


Figure 5: Scenario 1: Low complementarity scenario and the CRM-system maximum price less than the N-system maximum price

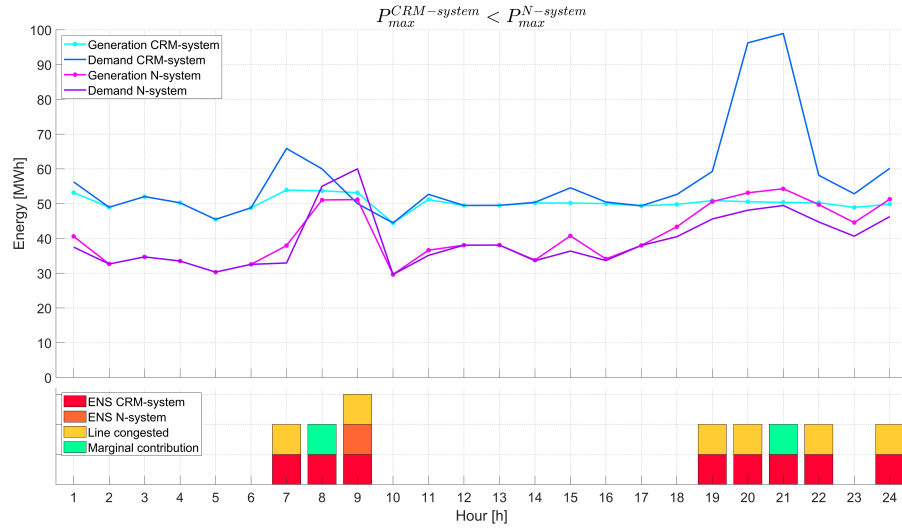


Figure 6: Scenario 2: High complementarity scenario and the CRM-system maximum price less than the N-system maximum price

| Scenario | ENS<br>Baseline<br>[MW] | ENS<br>Stepwise<br>Reference<br>[MW] | ENS<br>Stepwise<br>Resource<br>[MW] | Reference<br>Contribution<br>[MW] | Resource<br>Contribution<br>[MW] | De-rating<br>factor<br>[%] |
|----------|-------------------------|--------------------------------------|-------------------------------------|-----------------------------------|----------------------------------|----------------------------|
| 1-Low    | 123.4858                | 123.4778                             | 123.4818                            | 0.008                             | 0.004                            | 50                         |
| 2-High   | 110.0303                | 110.0223                             | 110.0283                            | 0.008                             | 0.002                            | 25                         |

Table 3: Classification by the hour and cross-border de-rating factors for Case 1A.

On the other hand, Table 3 below shows in columns the results obtained for the CRM-system in both low and high complementarity scenarios when the generalized methodology is applied: ENS in the baseline scenario, ENS after increasing the reference asset’s capacity, ENS after increasing the cross-border resource’s capacity, the total number of hours with ENS in the baseline, the hours in which the N-system makes marginal contributions, and the cross-border de-rating factor. The results in Table 3 show that, as expected, having resources with high complementary reduces the ENS in the CRM-system. However, it reduces the cross-border de-rating factor. This is because when resources are complementary, the market naturally maximizes energy exports from the N-system to the CRM-system until the interconnection is saturated without relying on the CRM. This effect can be seen comparing the generation in hours 20 and 24 in Figures 1.2 and 1.3. As a result, the incentive for the N-system resources to participate in the cross-border mechanism is reduced due to the saturation of the interconnection. Finally, observe that the results obtained with the step-by-step and generalized methodologies match, validating both approaches.

### 5.1.2 Case 1B: The CRM-system maximum price equals the N-system maximum price

Figures 7 and 8 present the main results for the low and high complementarity scenarios, assuming the CRM-system maximum price equals the N-system maximum price. The nomenclature and the test system are consistent with the previous case. However, gray bars have been included to highlight the hours during which there could be marginal contributions from the N-system, depending on the allocation rule, as shown at hour 8 in both figures. In this case study, it is assumed that the allocation rule guarantees cross-border delivery from the N-system resources, even in the presence of ENS in the N-system. Similar to the previous case, it is evident that high complementarity increases the saturation of the interconnection (refer to hours 20 and 24 in both figures) and results in fewer hours with marginal contributions from the N-system (refer to hours 20, 21, and 24 in both figures). Furthermore, there are more coincident hours of ENS in both areas in the high complementarity scenario (hours 8 and 9), which impacts the reliability of the CRM-system. However, this impact could be mitigated if cross-border delivery from the N-system resources is guaranteed with the allocation rule.

Similar to Table 3, Table 4 presents the results for the CRM-system in both the low and high complementarity scenarios using the generalized methodology. The results confirm that higher complementarity between resources reduces ENS in the CRM-system and lowers the cross-border de-rating factor. The table also highlights the significant impact allocation rules can have on de-rating factors. For instance, under low complementarity, the de-rating factor ranges from 42.9%, when flows from the N-system to the CRM-system are restricted during scarcity in the N-system, to 57.1% when such flows are allowed. A similar pattern is observed in the high complementarity scenario, where contributions range from 12.5% to 37.5%. These results suggest that well-designed allocation rules can incentivize greater cross-border participation in CRMs. Finally, it is worth mentioning that the results obtained with the step-by-step and generalized methodologies match again.

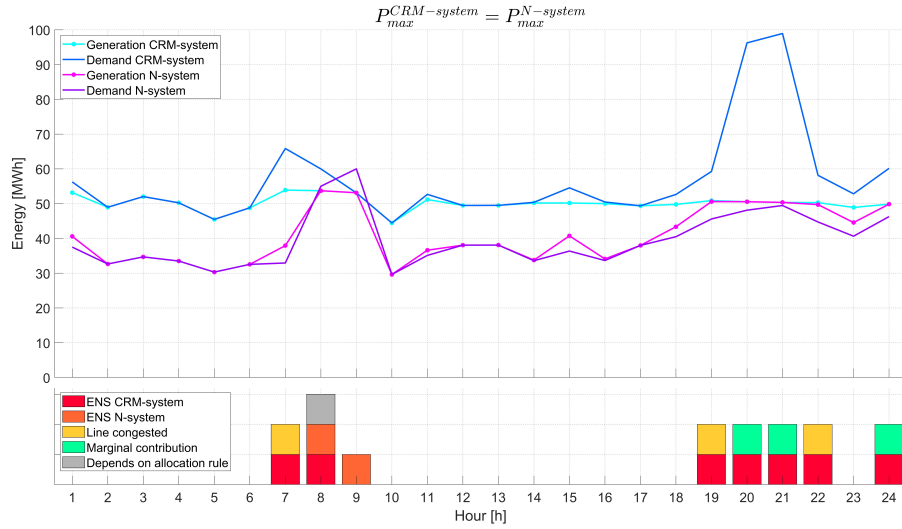


Figure 7: Scenario 1. Low complementarity scenario and the CRM-system maximum price equals the N-system maximum price

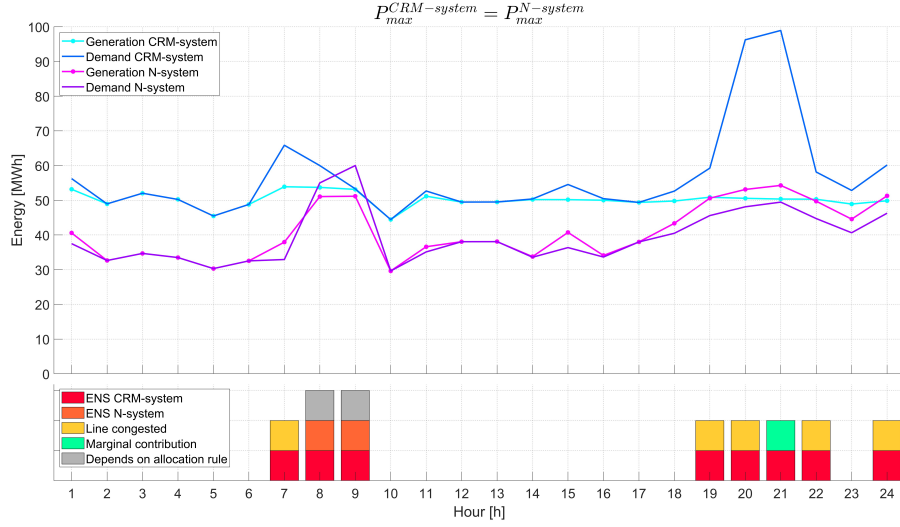


Figure 8: Scenario 2. High complementarity scenario and the CRM-system maximum price equals the N-system maximum price

| Scenario | ENS Baseline [MW] | ENS Stepwise Reference [MW] | ENS Stepwise Resource [MW] | Reference Contribution [MW] | Resource Contribution [MW] | De-rating factor [%] |
|----------|-------------------|-----------------------------|----------------------------|-----------------------------|----------------------------|----------------------|
| 1-Low    | 117.1300          | 117.1230                    | 117.1270                   | 0.0070                      | 0.0030                     | 42.9 or 57.1         |
| 2-High   | 109.2936          | 109.2856                    | 109.2926                   | 0.0080                      | 0.0010                     | 12.5 or 37.5         |

Table 4: Classification by the hour and cross-border de-rating factors for Case 1B.

| Complementarity | Capacity [GW] | ENS [MW] | Hours with ENS | Hours with Marg. Cont. | Cross-border de-rating factor [%] |
|-----------------|---------------|----------|----------------|------------------------|-----------------------------------|
| Low             | 2.5           | 126.7    | 9              | 2 or 3                 | 22.2 or 33.3                      |
|                 | 5.0           | 117.13   | 7              | 3 or 4                 | 42.9 or 57.1                      |
|                 | 7.5           | 113.78   | 7              | 5 or 6                 | 71.4 or 85.7                      |
|                 | 10            | 111.28   | 7              | 5 or 6                 | 71.4 or 85.7                      |
| High            | 2.5           | 125.1    | 10             | 0 or 2                 | 0 or 20                           |
|                 | 5.0           | 109.3    | 8              | 1 or 3                 | 12.5 or 37.5                      |
|                 | 7.5           | 98.14    | 8              | 2 or 4                 | 25 or 50                          |
|                 | 10            | 93.85    | 6              | 3 or 5                 | 50 or 83.3                        |

Table 5: ENS and cross-border de-rating factors under different scenarios for the interconnection capacity.

### 5.1.3 Case 1c: Effects of the capacity of the interconnection

The previous cases assumed a maximum interconnection capacity of 5 GW. This case study conducts a sensitivity analysis to evaluate the impact of transmission capacity on recognized cross-border de-rating factors. The analysis considers scenarios with the CRM-system maximum price as equal to the N-system maximum price and low and high complementarity. This scenario was chosen to identify both actual contributions and potential contributions based on the allocation rule. Table 5 columns display the scenario, line capacity, ENS, total hours with ENS in the CRM-system area, hours with marginal contributions from the N-system area, and calculated cross-border de-rating factor. As expected, the table shows that increasing interconnection capacity improves the CRM-system area reliability. Furthermore, interconnection capacity significantly affects recognized cross-border de-rating factors. The results indicate that increasing the line capacity by four times could significantly boost cross-border de-rating factors, increasing by more than 49% irrespective of the allocation rule applied. Additionally, results suggest that implementing an allocation rule ensuring energy delivery to the CRM could create additional incentives for cross-border participation, ranging from 11% to 33%.

## 5.2 Case 2: Impacts of resource uncertainty on firm supply and resource adequacy

This case study explores the impacts of resource uncertainty on firm supply using a more realistic approach than the previous case. A horizon of 8.760 hours is considered, and 100 correlated wind power pathways are simulated for each area using the methodology from [26]. The technical data for the generators remains the same as in Case 1, with the interconnection capacity set at 5GW. However, unlike Case 1, which focused on CCGT technologies participating in the cross-border CRM, this case considers wind resources as participants. This change means that the contributions of cross-border resources vary each hour, depending on resource availability. In capacity-constrained power systems, for instance, de-rating factors for wind resources could range from 10% to 33% [27], with these variations likely influenced by differing scarcity conditions and resource availability in each system. As a result, in contrast to the CCGT example in Case 1, where a 1 MW capacity could contribute 1 MWh under favorable system conditions, wind resources are expected to deliver lower firm contributions for the same installed capacity due to their inherent variability.

Moreover, this case study examines how establishing the adequacy assessment at different distribution percentiles could affect cross-border de-rating factors. The purpose of this analysis is twofold. On the one hand, identifying whether CRM would offer more incentives to new resources. On the other hand, it analyzes the dependency of the methodology on calculating cross-border de-rating factors when the uncertainty of renewable resources is considered. Finally, as in Case 1, two maximum price scenarios have been simulated: 1. The maxi-

imum price in the CRM-system is assumed to be lower than in the N-system, and 2. The maximum price in the CRM-system equals the N-system maximum price.

Figure 9 illustrates the probability density functions for the EENS in the CRM-system area when the maximum price in the CRM-system is assumed to be lower than in the N-system. The cyan, blue, and magenta lines correspond to the ENS results from the baseline, a stepwise increase in the wind resource, and a stepwise increase in the reference asset, respectively. The vertical dotted lines indicate the expected EENS values for each scenario. Notice that if a resource with 100% availability were considered in the N-system, the blue line would be closer to the cyan line. As expected, given the small step size relative to the interconnection capacity and EENS, the three scenarios display only minor differences in the distribution shapes and their expected values. In fact, the figure highlights a narrow portion of the distribution, but it still provides insight into the overall trend.

In contrast to Figure 9, Table 6 presents the EENS values and de-rating factors for wind technologies participating in the CRM across the three scenarios, evaluated at various percentiles. An additional column is included at the end of the table to show the results when CCGT is considered<sup>3</sup> as a cross-border resource, for comparison purposes. The results were obtained by considering the 100 wind scenarios. Additionally, the table provides at the bottom results for Conditional Value at Risk (CVaR) [28], calculated for the 5% least favorable scenarios, and the Expected Value (E.V.). Based on these results, it can be seen that the cross-border de-rating factor varies between 12.11% and 14.98% for wind, depending on the selected metric, which is coherent with the results obtained in the literature [27]. In comparison, de-rating factors for the CCGT oscillate between 59.19% and 60.58%, following the behavior obtained in Case 1. The disparity in de-rating factors between wind and CCGTs stems from wind's lower utilization rate, as its availability fluctuates, compared to the consistently high utilization of CCGTs, which are always available. In addition, results show that RES uncertainty significantly impacts the volatility of de-rating factors for wind technologies while having a much lower effect on the variation of the CCGT's de-rating factors.

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<sup>3</sup>The distribution function results when CCGT is considered were excluded from Figure 9 as they did not provide additional valuable insights and would have unnecessarily complicated the figure.

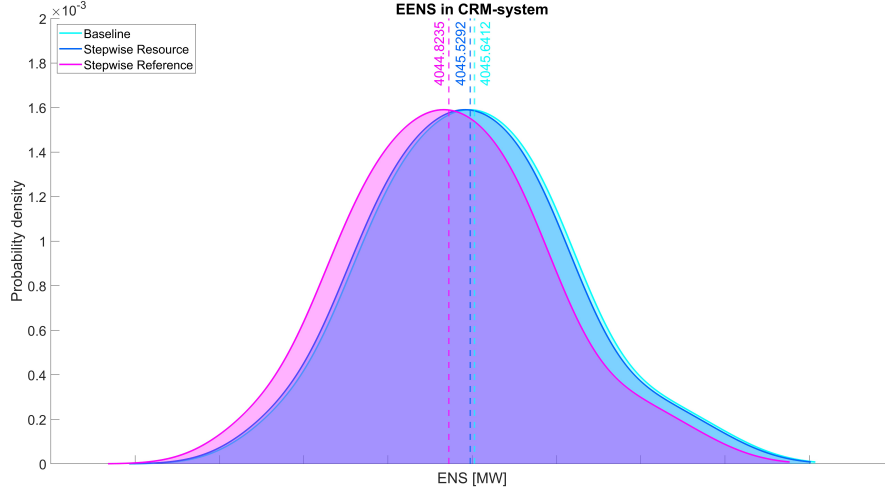


Figure 9: Probability density when the maximum price in the CRM-system is assumed to be lower than in the N-system

| Percentil | EENS<br>Baseline<br>[MWh] | EENS<br>Stepwise<br>Reference<br>[MWh] | EENS<br>Stepwise<br>Resource<br>[MWh] | Cross-border<br>de-rating factor<br>(Wind)<br>[%] | Cross-border<br>de-rating factor<br>(CCGT)<br>[%] |
|-----------|---------------------------|----------------------------------------|---------------------------------------|---------------------------------------------------|---------------------------------------------------|
| P05       | 3688.34                   | 3687.57                                | 3688.23                               | 14.98                                             | 59.70                                             |
| P25       | 3877.59                   | 3876.79                                | 3877.47                               | 14.57                                             | 59.36                                             |
| P50       | 4028.60                   | 4027.80                                | 4028.49                               | 13.64                                             | 60.58                                             |
| P75       | 4190.06                   | 4189.23                                | 4189.95                               | 13.35                                             | 59.19                                             |
| P95       | 4488.80                   | 4487.92                                | 4488.69                               | 12.15                                             | 59.24                                             |
| CVaR      | 4559.96                   | 4559.09                                | 4559.86                               | 12.11                                             | 59.35                                             |
| E.V.      | 4045.64                   | 4044.82                                | 4045.53                               | 13.70                                             | 59.96                                             |

Table 6: EENS and cross-border de-rating factors when the maximum price in the CRM-system is assumed to be lower than in the N-system under different percentiles.

Figure 10 illustrates the probability density functions for the EENS in the CRM-system area when The maximum price in the CRM-system equals the N-system maximum price. In this case study, it is assumed that the allocation rule guarantees cross-border delivery from the N-system resources, even in the presence of ENS in the N-system. The nomenclature and results follow the same format as the previous case. In addition, Table 7 shows the EENS values and de-rating factors for wind and CCGT technologies across different percentiles, along with the CVaR and E.V. It is clear that the EENS decreases with percentiles for both technologies compared to the results obtained in the previous case. The recognized cross-border de-rating factor ranges from 5.02% to 5.87% for wind and from 19.92% to 22.64% for CCGT, depending on the chosen met-

ric. Notably, wind exhibits less variability across percentiles than CCGT, which contrasts with the findings from the previous case. A trend can be observed in Tables 6 and 7, showing that CVaR tends to result in lower cross-border de-rating factors.

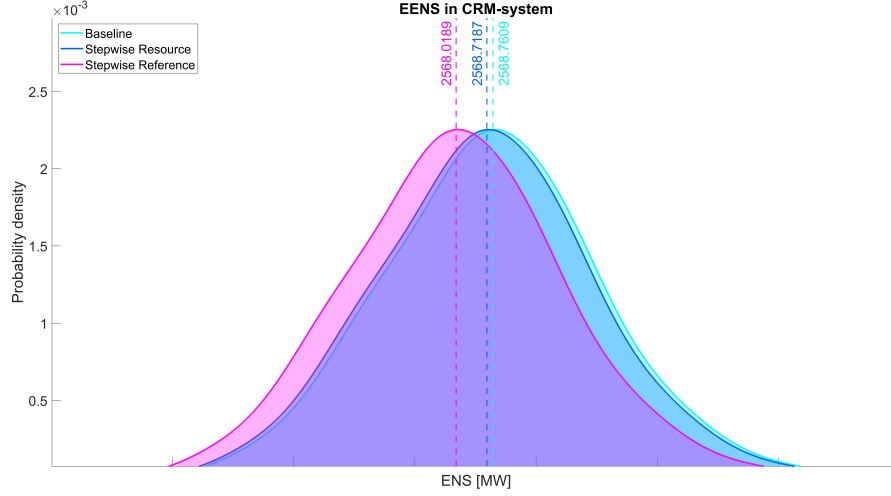


Figure 10: Probability density when the maximum price in the CRM-system equals the N-system maximum price.

| Percentil | EENS<br>Baseline<br>[MWh] | EENS<br>Stepwise<br>Reference<br>[MWh] | EENS<br>Stepwise<br>Resource<br>[MWh] | Cross-border<br>de-rating factor<br>(Wind)<br>[%] | Cross-border<br>de-rating factor<br>(CCGT)<br>[%] |
|-----------|---------------------------|----------------------------------------|---------------------------------------|---------------------------------------------------|---------------------------------------------------|
| P05       | 2304.82                   | 2304.11                                | 2304.79                               | 5.18                                              | 19.92                                             |
| P25       | 2454.27                   | 2453.53                                | 2454.23                               | 5.45                                              | 21.70                                             |
| P50       | 2558.19                   | 2557.45                                | 2558.15                               | 5.77                                              | 21.88                                             |
| P75       | 2683.05                   | 2682.30                                | 2683.01                               | 5.87                                              | 22.64                                             |
| P95       | 2846.37                   | 2845.57                                | 2846.33                               | 5.30                                              | 21.26                                             |
| CVaR      | 2933.47                   | 2932.69                                | 2933.43                               | 5.02                                              | 20.99                                             |
| E.V.      | 2568.76                   | 2568.02                                | 2568.72                               | 5.69                                              | 21.50                                             |

Table 7: EENS and cross-border de-rating factors when the maximum price in the CRM-system equals the N-system maximum price under different percentiles.

## 6 Conclusions

This paper explores the key determinants shaping the firm supply of cross-border resources in CRMs, a topic that remains underdeveloped in the litera-

ture within regional contexts. To that end, a generalized methodology is introduced as theoretical framework to systematically identify and quantify the contribution of foreign resources to de-rating factors in regional contexts. The methodology serves to highlight the importance of factors such as maximum national prices, interconnection capacity, and resource complementarity in determining cross-border de-rating factors. Through detailed case studies, the analysis demonstrates how these factors interact in practice. For example, the results show that when a system with a CRM in place has a higher maximum price than its neighboring country, cross-border resources may contribute to overall reliability without being recognized as firm capacity due to congestion during scarcity periods. Similarly, although resource complementarity between areas improves overall adequacy, it can reduce marginal contributions and thus lower the de-rating factors attributed to foreign resources. In one illustrative case, a high complementarity between the wind profiles of two areas led to a drop in recognized firm supply from 50% to 25%. These effects are magnified or mitigated depending on the interconnection capacity and the specific allocation rules adopted during coincident scarcity events. The results also show that the design of allocation rules plays a pivotal role in determining whether and how foreign resources can effectively participate in CRMs. Specifically, the results show that when allocation rules guarantee the delivery of contracted capacity across borders, even during simultaneous scarcities, recognized firm supply increases significantly. For instance, in a stylized case with equal maximum prices, the de-rating factor of a foreign generator increased by more than 30% when a favorable allocation rule was in place.

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## 8 Annex I: Derivation of equation

This appendix demonstrates the relationship between the contribution of resource  $i$  to the reliability of market  $j$  as expressed in equation (1). The process is carried out in three steps. First, the profit-maximization problem for individual producers is formulated and solved. Then, a simplified optimization problem is addressed, representing a centralized planning scenario where no transmission network constraints are imposed. By comparing the results from these two approaches, the derivation of equation (1) becomes clear.

Nomenclature:

|                |                                                                                         |
|----------------|-----------------------------------------------------------------------------------------|
| $M$            | Total number of markets.                                                                |
| $\Psi$         | Net social benefit across all markets.                                                  |
| $\Pi_i^j$      | Profits of generation unit $i$ located in market $j$ .                                  |
| $q_i^j$        | Generation level of unit $i$ in market $j$ .                                            |
| $k_i^j$        | Capacity of unit $i$ assigned to the CRM of market $j$ .                                |
| $C(\cdot)$     | Generation cost function.                                                               |
| $I(\cdot)$     | Investment cost function.                                                               |
| $U(\cdot)$     | Demand utility function.                                                                |
| $RM^j(\cdot)$  | Reliability metric used in market $j$ .                                                 |
| $RT^j$         | Reliability target in market $j$ .                                                      |
| $\alpha_i^j$   | Lagrange multiplier associated with the capacity constraint of unit $i$ in market $j$ . |
| $\beta^j$      | Lagrange multiplier associated with the minimum reliability constraint in market $j$ .  |
| $\kappa_i$     | Total capacity of unit $i$ installed to be remunerated in all CRMs.                     |
| $\lambda_i^j$  | Spot market price received by unit $i$ in market $j$ .                                  |
| $\rho_i^j$     | Remuneration received by unit $i$ for participating in the CRM of market $j$ .          |
| $\mathbf{q}^j$ | Vector of the generation levels of all units in market $j$ .                            |
| $\mathbf{k}^j$ | Vector of the capacities assigned to the CRM of market $j$ .                            |
| $\mathbf{Q}$   | Vector of generation levels across all units in all markets.                            |
| $\mathbf{K}$   | Vector of capacities assigned to all CRMs across markets.                               |

### 8.1 First step: The individual agent problem

This section introduces a model designed for a regional system, where firms aim to maximize their profits across both the spot and capacity markets. Inspired by the framework outlined in [6] and [25], the proposed model is shown through equations (3) and (4). Within this model, the problem tackled by unit  $i$  located in market  $j$  is formulated as follows:

$$\max_{q_i^j, k_i^j} \Pi_i^j = \lambda_i^j q_i^j + \sum_{m=1}^M k_i^m \rho_i^m - C_i^j(q_i^j) - I_i^j(\kappa_i^j) \quad (3)$$

subject to:

$$q_i^j \leq \kappa_i^j \quad (4)$$

where:

$$\kappa_i^j = \sum_{m=1}^M k_i^m \quad (5)$$

$$I(\kappa_i^j) = I_i^1(k_i^1) + I_i^2(k_i^2) + \dots + I_i^M(k_i^M) \quad (6)$$

In (3), the first term represents the incomes perceived by unit  $i$  for selling the quantity  $q_i^j$  at a per-unit price  $\lambda_i^j$  in the spot market  $j$  where it is located. The second term refers to the incomes of unit  $i$  for participating in the CRM of all the markets. In this case, it is assumed that the market  $m$  recognizes an installed capacity of  $k_i^m$  at a per-unit price  $\rho_i^m$  to be remunerated into the CRM. The third and fourth terms represent the operation and investment cost of unit  $i$ . Likewise, equation (4) guarantees that the generation does not exceed the installed capacity. It should also be noted that the total installed capacity  $\kappa_i^j$  is the sum of the capacities allocated to each capacity market, as indicated in equation (5). Finally, the total investment cost is the aggregate of the costs associated with the installed capacities across all markets for adequacy services, as shown in equation (6).

The optimal solution to the centralized problem must meet the first-order conditions. To derive these conditions, the Lagrangian function is formulated as follows:

$$L(q_i^k, k_i^j, \alpha_i^j) = \lambda_i^j q_i^j + \sum_{m=1}^M k_i^m \rho_i^m - C_i^j(q_i^j) - I_i^j(\kappa_i^j) + \left( q_i^j - \sum_{j=1}^M k_i^j \right) \alpha_i^j \quad (7)$$

When computing the first partial derivative of this expression concerning the decision variable  $k_i^j$ , the following expression is obtained:

$$\frac{\partial L}{\partial k_i^j} = \rho_i^j - \frac{\partial I_i^j(k_i^j)}{\partial k_i^j} - \alpha_i^j = 0 \quad (8)$$

## 8.2 Second Step: Centralized problem

In the simplified, centralized problem, new generators are allocated centrally, with the security targets of each market taken into account. Generation units from any market can participate in the CRMs of other electricity markets, with transmission constraints deliberately excluded to ensure fair competition among capacity providers. This means that grid limitations do not impact the entry of a generator into the system, creating a level playing field where transmission grid constraints do not influence generator participation. Within this framework, the simplified, centralized problem aims to maximize net social benefit and can be formulated as follows:

$$\max_{\mathbf{Q}, \mathbf{K}} \Psi = U(\mathbf{q}^1 + \mathbf{q}^2 + \dots + \mathbf{q}^M) - C(\mathbf{Q}) - I(\mathbf{K}) \quad (9)$$

subject to:

$$q_i^j \leq \kappa_i^j \quad \forall i, \forall j \quad (10)$$

$$RM^j(\mathbf{K}) \geq RT^j \quad \forall j \quad (11)$$

where  $\mathbf{Q} = (\mathbf{q}^1, \mathbf{q}^2, \dots, \mathbf{q}^M)$  and  $\mathbf{K} = (\mathbf{k}^1, \mathbf{k}^2, \dots, \mathbf{k}^M)$ . The objective of the central planner is to maximize the demand's profits and minimize the operation and investment system's costs. At the same time, the decision variables are the generation of the units and the new capacities to be installed in each market. The first constraint guarantees that the generation of the unit  $i$  does not exceed the installed capacity. Similarly, the second constraint guarantees that the reliability metric defined by each area is accomplished in the solution. As in the individual agent problem, the optimal solution to the centralized problem must meet the first-order conditions. In this context, the Lagrange function  $L$  is given by:

$$L(\mathbf{Q}, \mathbf{K}, \alpha, \beta) = U(\mathbf{q}^1 + \mathbf{q}^2 + \dots + \mathbf{q}^M) - C(\mathbf{Q}) - I(\mathbf{K}) + \sum_{\forall i, j} (q_i^j - \kappa_i^j) \alpha_i^j + \sum_{j=1}^M (RM^j(\mathbf{K}) - RT^j) \beta^j \quad (12)$$

and the first partial derivative of equation (12) with respect to the decision variable  $\kappa_i^j$ , i.e., regarding the installed capacity of unit  $i$  located at market  $j$ , it is obtained that:

$$\frac{\partial L}{\partial \kappa_i^j} = -\frac{\partial I(\kappa_i^j)}{\partial \kappa_i^j} - \alpha_i^j + \frac{\partial RM^j(\mathbf{K})}{\partial \kappa_i^j} \beta^j = 0 \quad (13)$$

The first two terms in the equation are the balance between short-term savings and the increase in long-term at the optimal point. In contrast, notice that the third term will only be present when an adequacy problem exists in the market  $j$ , i.e., when the constraint given by equation (11) is active.

### 8.3 Third step: Outcomes comparison

If the investment cost is linear, it remains constant regardless of the installed capacities within each CRM. In other words, the cost of expanding unit  $i$  in market  $j$  does not depend on the capacity recognized in the CRMs. Mathematically, this can be expressed as:

$$I_i^j(k_i^j) = k_i^j IC_i \quad \forall i, j \quad (14)$$

Therefore, it can be shown from equation (6) that:

$$I(\kappa_i^j) = \kappa_i^j IC_i \quad (15)$$

In addition, it can be identified from equations (14) and (15) that:

$$\frac{\partial I(k_i^j)}{\partial k_i^j} = \frac{\partial I(\kappa_i^j)}{\partial \kappa_i^j} = IC_i \quad (16)$$

Comparing equation (8) and equation (13), we obtain the optimal per-unit remuneration for the new resource  $i$  located in market  $j$ , for its contributions to the reliability metric of the market  $j$ :

$$\rho_i^j = \frac{\partial RM^j(\mathbf{K})}{\partial \kappa_i^j} \beta^j \quad (17)$$

where  $\frac{\partial RM^j(\mathbf{K})}{\partial \kappa_i^j}$  is the marginal contribution of resource  $i$  to the reliability of market  $j$ , denoted by  $\Phi_i^j$ . Notice also that the last expression is optimal for the centralized planner and firms.

## 9 The medium-term generation planning model

The primary contribution of this paper is the introduction of a new methodology for allocating firm supply in a regional context. A medium-term generation planning model, inspired by the work of [29], is employed to evaluate this methodology. The key components of this model are presented in equations (18)-(21):

$$\min \sum_{m \in M} \sum_{t \in T} \sum_{g \in m} OC_{t,g}^m + \sum_{m \in M} \sum_{t \in T} ENS_t^m NC^m \quad (18)$$

subject to:

$$\sum_{g \in m} P_{t,g}^m + ENS_t^m = D_t^m + \sum_{\substack{n \in M \\ n \neq m}} (F_t^{n,m} - F_t^{m,n}) \quad \forall m, t \quad (19)$$

$$-\bar{F}^{n,m} \leq F_t^{n,m} \leq \bar{F}^{n,m} \quad \forall n, m \in M, n < m \quad (20)$$

$$\mathcal{H}(P_{t,g}^m) \geq 0 \quad \forall g, m, t \quad (21)$$

Equation (18) defines the objective of the centralized planner, which aims to minimize the total costs, including both operational costs and Energy Not Served (ENS) costs. Operational costs account for the maintenance and variable expenses of thermal units. Equation (19) represents the balance equation, ensuring supply and demand equilibrium for each market and period. Equation (20) incorporates power flow limits on transmission lines connecting the markets, while expression (21) outlines additional technical and economic constraints, such as unit operational limits, hydro-thermal resource allocation throughout the planning horizon, and thermal resource scheduling. It is important to note that the proposed methodology is adaptable and not restricted to this particular optimization model. It can be applied to other medium-term generation planning models as described in [30] and adjusted to accommodate various adequacy metrics.

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