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Emma Menegatti, Leonardo Meeus

European University Institute
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Abstract

Capacity mechanisms are gaining momentum in Europe, and the latest EU electricity market reform further reinforces their role. The negative externalities exerted by these national mechanisms in interconnected zones might, therefore, become a growing issue. With the hope of mitigating cross-border externalities, EU regulation requires Member States with a capacity market to enable the explicit participation from resources located in neighboring Member States. However, the effectiveness of this rule in reducing externalities hasn't been conclusively established. In this paper, we assess the effectiveness of "explicit" and "implicit" cross-border participation in addressing the externalities of a national capacity market on a neighboring system without any capacity mechanism. We use an equilibrium model formulation representing a stylized electricity system of two zones. We have two conclusions, based on three findings. First finding, cross-border participation does not entirely mitigate the externalities of the capacity market on neighboring consumers, generators and the interconnector. Second finding, implicit and explicit cross-border participation yield equivalent results. Third finding, the cross-border effects of national capacity mechanisms can prevent them from effectively achieving their very objective - ensuring security of supply. Based on the first and the third findings, we conclude for the medium term that we will need to evolve from national capacity markets towards a Europeanized adequacy mechanism to effectively ensure security of supply and avoid cross-border effects. Based on the second finding, we have a shorter-term conclusion for the objective of the latest electricity market reform to streamline the implementation of capacity mechanisms at the national level. Because implicit is simpler than explicit cross-border participation, and they both equally mitigate externalities in the energy-only zone, we could consider moving from explicit to implicit cross-border participation in capacity markets.

Keywords

Electricity, Market design, Adequacy, Capacity mechanisms

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1. Introduction

Capacity Mechanisms have gained momentum in Europe and may be here to stay. The EU market design reform of 2024 further reinforces their role, and the European Resource Adequacy Assessment of ENTSO-E (2023) foresees adequacy issues persisting or appearing in a number of Member States by 2033. The EU electricity markets have today a patchwork of different mechanisms including strategic reserves (Germany, Finland, Sweden), and capacity markets (Belgium, France, Ireland, Italy, Poland), while other countries continue to rely on the investment signals of the “Energy-Only” market for resource adequacy. In this paper, we reflect on the inefficiencies arising at the multi-jurisdictional level from such heterogeneity, and the potential of cross-border arrangements to mitigate them.

The need for capacity mechanisms to complement the energy markets has been widely discussed in the literature and remains controversial. Their interest was for example shown by Hobbs et al. (2001), Joskow & Tirole (2007), Fabra (2018) in the presence of price caps and market power; by De Vries & Heijnen (2008) with demand growth uncertainty; by Bhagwat et al. (2017) with a high renewable penetration; by Cepeda & Finon (2013) in the presence of renewable subsidies; and by Petitet et al. (2017), Fraunholz et al. (2023) with investors’ risk-aversion. In practice, the concerns raised by European TSOs to justify the introduction of national capacity mechanisms have been diverse, as detailed by Papavasiliou (2021) and Roques & Verhaeghe (2022), including notably the missing money issue, the unpredictability of the peak demand, and the public good nature of electricity. The optimal design of capacity mechanisms also remains widely debated. For instance, Vázquez & al. (2002), Cramton & Stoft (2008) have argued for reliability options, Joskow (2008) showed the interest of capacity obligations, and Finon & al. (2008) discusses the efficiency of strategic reserves.[1] Though most analyses take a national perspective, European solutions have been considered, such as a European strategic reserve by Neuhoff & al. (2016), or an integrated capacity market by SWECO (2014) and Bucksteeg et al. (2019). In practice, the Electricity Regulation (2019) allows for the national-level implementation of strategic reserves, and as a second choice, capacity markets. In the following, we focus on capacity markets. They are already the most widespread form of capacity mechanism in the EU. Strategic reserves are expected to lose ground, as two[2] out of the three Member States operating only such a reserve are considering moving towards a capacity market over the coming decade. Capacity markets are moreover the most prone to cross-border externalities.

Capacity markets have historically tended to underestimate the contribution of imports[3], thereby overshooting their local capacity needs. Such a push towards electricity supply “autarky” can eventually result in high costs at the EU level, as highlighted notably in reports by ACER (2013) and European Commission (2016). The capacity saved in Europe in a scenario where capacity demand is defined cooperatively rather than nationally, was estimated at around 6% by Hagspiel et al. (2018), and 10% by Bucksteeg et al. (2019). This can be resolved simply by deducting imports from the local capacity demand, i.e. implementing implicit cross-border participation, or by allowing resources from neighboring systems to bid into the capacity market, i.e. implementing explicit cross-border participation.

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[1] Alternatives solutions to restore investment incentives are also debated such as energy call-options obligations in Oren (2005), scarcity pricing through operating reserves in Hogan (2013), and fostering forward markets in Ausubel & Cramton (2010)

[2] Sweden is expected to introduce a capacity market, as announced by Svenska Kraftnät (2023). Germany is also expected to implement a capacity market as described by the BMWK (2024).

[3] The underestimation of imports can be explained by multiple factors. First, some factors can be political, including distrust in neighbors or a will to achieve security of supply independently. Second, some factors are more practical. A TSO does not have control, nor complete oversight, over the foreign resources’ schedules and availability (including generators, demand response, and internal lines). Third, uncertainty also comes into play. If concomitant scarcity periods are likely, both zones might overestimate the likelihood of such events. Finally, the availability of imports depends on the available cross-border capacity, which can be limited due to various technical and security issues such as internal congestion.

Capacity markets were historically only opened to domestic resources. Foreign resources and interconnectors were not able to receive remuneration for the same service provided. This difference of treatment goes against the non-discrimination principle in EU law. Therefore, rules to allow non-domestic resources to participate in capacity markets were gradually implemented. Explicit participation by interconnectors has been used temporarily in a number of Member States. Following the Clean Energy Package, the explicit cross-border participation rule was made mandatory for all market-wide capacity mechanisms, see Electricity Regulation (2019). The implementation of this rule is however lagging, as highlighted by ACER (2023). The Irish capacity market still applies the implicit approach, while the French capacity market applies explicit participation by interconnectors. Explicit cross-border participation, as foreseen in the Clean Energy Package, is today implemented only in the Polish, Italian (with a simplified approach), and Belgian (first auction in 2024) capacity markets.

In this paper, we examine the impact of cross-border participation on four types of cross-border externalities exerted by a country or zone with a capacity market on a neighboring country or zone without any capacity mechanism, which are described in the following paragraphs by referring to the relevant academic literature.

First is the displacement of generation capacities from the neighboring zone, to the zone with a capacity market. This issue was observed and described in a few quantitative studies such as Höschle et al. (2016), Bucksteeg et al. (2019) using equilibrium or optimization models, Bhagwat et al. (2017), Fraunholz et al. (2021), Cepeda & Finon (2011) using agent-based or system dynamics models, and Lambin & Léautier (2019), Meyer & Gore (2015) using analytical approaches[4]. The capacity market tends to reduce energy prices in the zone where it is implemented, and eventually in the neighboring zones through exports. This, in turn, can reduce the investment incentives and the generation capacity installed in the long run in the neighboring zone.

Second is the increase in consumers' costs in the neighboring zone. The displacement of capacity and distortion of cross-border trade induced by the introduction of a capacity market in one zone eventually affects the consumers' costs in neighboring zones. Total costs, including unserved energy costs, were found for example to be increasing in the zone without any capacity mechanism, and decreasing in the zone with a capacity market, by Höschle et al. (2016). Such an asymmetrical allocation of the capacity market's costs appears problematic.

Third is the reduction of security of supply in the neighboring zone. The displacement of capacity can result in increasing unserved energy, as observed in modelling studies using long-term equilibrium or optimization models such as Bucksteeg et al. (2019), SWECO (2014), and Höschle et al. (2016). As highlighted by Lambin & Léautier (2019), this issue might lead to a domino effect, where implementing a capacity market in one zone incentivizes the introduction of capacity mechanisms in neighboring zones.

Fourth is the distortion of congestion revenues on the interconnector between the two zones. Implementing a capacity market affects energy prices and therefore cross-border trade and interconnectors' revenues. Whether the congestion revenues' distortion is positive or negative appears to depend on the initial trade balance of the zone implementing a capacity market, as observed in SWECO (2014). A negative distortion can hinder investments in interconnection capacity, which was one of the reasons to implement explicit participation rules to directly or indirectly remunerate interconnectors. A positive distortion incentivizing more investments in interconnectors can increase the generation capacity displacement effect.

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[4] To our knowledge, there is no empirical study revealing real cases of such effects occuring in the EU. It might be difficult to observe in practice, because the capacity displacement effect occurs in the long term, and because Member States foreseeing adequacy issues are likely to implement a capacity mechanism before the effect is visible or problematic.

Our main contribution is assessing the ability of cross-border participation to mitigate the four types of cross-border externalities of a capacity market described above, which has not yet been done systematically. Mengerink (2021), Finon (2018) and E3M-Lab (2017) are three exceptions, but their analysis is limited. The first only provides specific numerical examples, the second is a conceptual paper, and the third is a study commissioned by the European Commission to support the impact assessment of the Clean Energy Package that introduced cross-border participation requirements in capacity markets. The first two argue that explicit cross-border participation fails to restore investment incentives abroad. The third is more positive about explicit cross-border participation, but we have questions about their methodology. In this paper we compare the performance of applying explicit, implicit and no cross-border participation. We provide an in-depth assessment by building on a state-of-the-art equilibrium model that has been used to analyze other aspects of capacity markets, in Höschle et al. (2016) (2018).

We believe this is a timely contribution because the latest electricity market reform requires the European Commission to identify possibilities to streamline the implementation of capacity mechanisms. If explicit cross-border participation is not effective, or not more effective than the simpler implicit cross-border participation rule, this change can be considered as part of the streamlining exercise.

In the next sections of this paper, we first introduce our mathematical model (section 2). We then assess the ability of explicit cross-border participation rules to mitigate the four cross-border effects described above, relying on our numerical simulations for a stylized power system (section 3). We follow by discussing these results and the model’s limitations (section 4). Finally, we highlight our main findings in the conclusion section (section 5).

2. Model description

In this section, we first position our modelling approach in the relevant literature. Second, we describe our equilibrium model set-up through the agents' optimization problems and additional constraints. Third, we describe our data input assumptions.

2.1 Modelling choices

We found numerous modelling studies focused on capacity mechanisms in a multi-jurisdictional set-up, and in particular evaluating capacity market's cross-border effects. We provide an overview of this literature in Table 1, and use it to position our key modeling choices. We discuss the different columns of the table in the following paragraphs.

Table 1 - Overview of existing literature on the cross-border effects of capacity remuneration mechanisms.

	Type	Cross border participation	Capacity mechanism rationale (market flaw)	Capacity mechanism type
(Fraunholz, Bublitz, Keles, & Fichtner, 2021) "National CRMs" scenario	Agent-based model	No	SoS overshoot	Heterogeneous EU mechanisms
(Lambin & Léautier, 2019)	Analytical	No	SoS overshoot Export restrictions	Capacity market Strategic reserve
(Bucksteeg, Spiecker, & Weber, 2019) "ASYM" scenario	Numerical optimization model	No	SoS overshoot	Capacity markets
(Höschle, Le Cadre, & Belmans, 2018)	Numerical equilibrium model	implicit explicit	SoS restored (Price cap)	Capacity market +Strategic reserve
(E3M-Lab, 2017)	?	implicit explicit	SoS restored (mark-up on SRMC)	Heterogeneous EU mechanisms
(Höschle, De Jonghe, Six, & Belmans, 2016)	Numerical equilibrium model	No	SoS overshoot	Capacity markets
(Meyer & Gore, 2015)	Theoretical equilibrium model	No	(Mark-up on SRMC)	Reliability options Strategic reserve
(Bhagwat, Richstein, Chappin, Iychettira, & De Vries, 2017)	Agent-based model	No	SoS overshoot SR activation < VOLL	Capacity market Strategic Reserve
(SWECO, 2014) « CPS » scenarios	Numerical optimization model	Form of implicit	SoS overshoot	Capacity Markets
(THEMA, EMLab, COWI, 2013)	Numerical optimization model	No	SoS overshoot	Capacity Payments
(Özdemir, de Joode, Koutstaal, & van Hout, 2013)	Optimisation and system dynamics	No	SoS overshoot	Capacity Market
(Cepeda & Finon, 2011)	System Dynamics	No	Price cap SoS overshoot	Capacity Market
Our model	Equilibrium model	No implicit explicit	SoS overshoot (sensitivity: Price cap)	Capacity Market

In the first two columns of the table, we refer to the authors, and the type of modelling approach applied. In the second column, we can distinguish between two main types of models, those representing short to medium-term reactions (agent-based, system dynamics) to compute a long-term reaction iteratively, and others focused rather on the long-term equilibrium without necessarily making assumptions on the agents' behavior (optimization or equilibrium models). The displacement of capacity from a zone without a capacity mechanism to a zone with a capacity mechanism was shown using all types of models. However, the reduction of security of supply observed in the zone without a capacity mechanism seem to only appear using the second type of models. We considered more appropriate to focus on long-term effects when studying capacity mechanisms, as they are about guiding investments. We therefore chose to implement an equilibrium model adapted from Höschle et al. (2016), in which the installed conventional capacity is a variable (i.e. not modified iteratively considering agent's behavior), which we expect will enable us to replicate the reduction of security of supply in the zone without a capacity mechanism.

In the third column, we observe that most authors did not analyze the cross-border participation rules, or only in a simplified manner. The only study implementing explicit cross-border participation with an equilibrium model is Höschle et al. (2016), but the authors did not systematically evaluate the measure. In E3M-Lab (2017), explicit and implicit cross-border participation were analyzed, but we disagree with the approach, because the two rules were combined in the capacity demand definition. We consider that imports should be either implicitly accounted for and deduced from the demand, or explicitly allowed to participate and not be deduced from the demand[5]. We chose to model the explicit cross-border participation rule through the introduction of a neighboring bidding zone in the capacity market, which is one of the two possibilities described in Mengerink (2021). The other alternative described by Mengerink is the auctioning of capacity entry tickets by the interconnector, but we considered that the outcome of such an approach using an equilibrium model would have been equivalent. Finally, we differentiate in our results two implementation options for explicit cross-border participation. In the first option, capacity congestion rents are not allocated, and consumers pay for capacity located in the neighboring bidding zone at the foreign capacity bidding zone price. In the second option, congestion revenues are allocated, and consumers pay for capacity located in the neighboring bidding zone at the local (rather than foreign) capacity bidding zone price. If the interconnection is congested, the additional payments are fully allocated to the interconnector as capacity congestion rents. According to ACER (2023), France, Italy and Belgium plan to follow the first option, while only Poland does allocate congestion revenues defined in the capacity market to the interconnector, calculated ex-post based on the clearing prices of the local and neighboring bidding zones. Note that the second option seems more in line with the Electricity Regulation, which mandates that the interconnector's capacity should be allocated in a market-based manner.

In the fourth column of the table, we illustrate an important assumption that each analysis on capacity markets makes regarding the need for such a mechanism. In papers that focus on the usefulness of a capacity mechanism, authors typically try to capture the energy-only market failures resulting in underinvestment. The imperfection of the energy-only market can be caused by a cap on wholesale electricity prices, market power, missing markets, uncertainty, investor's risk-aversion, investments' lumpiness, etc. The capacity market is then used to restore the optimal level of capacity, and can therefore be welfare improving. In other papers, the energy-only market imperfections are not included. In these papers, introducing a capacity market then implies targeting a specific reliability standard above the energy-only market equilibrium ("SoS overshoot") and resulting in overinvestment. The overinvestment can be justified by a political aversion to the risk of rationing due to shortages. In practice, numerous market failures as well as political risk-aversion may coexist, and justify the introduction of capacity markets. We follow the second approach because we focus on the assessment of cross-border participation rules, and therefore do not enter the debate on the

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[5] In practice, both rules could potentially co-exist, for example if some borders are considered implicitly and others explicitly. However, the implementation of both rules shouldn't overlap.

need for a capacity mechanism. In Appendix, we additionally provide the results of simulations in a scenario where the energy market is flawed by a price cap, and the capacity mechanism introduced in one zone aims to restore the optimal capacity level.

In the fifth column of the table, we indicate which capacity mechanisms are modeled in the papers we refer to. We model a market-wide mechanism, as this is the form currently mandated to implement explicit cross-border participation. Moreover, we design it as a centralized mechanism, which is the most common form in Europe (currently implemented in Belgium, Italy, Ireland and Poland). For simplicity, we model regular capacity market contracts rather than Reliability Options.

2.2 Equilibrium model formulation

As described in the previous section, we chose a long-run equilibrium model formulation. We adapt the model described in Höschle et al. (2016). In this section, we describe the optimization problems solved by individual agents and the additional constraints. They translate into a Mixed Complementarity Problem (MCP), described in Appendix. The dual variables are noted in brackets with the corresponding constraint. We compute equilibria using the PATH solver described in Munson & Ferris (1999) in Julia. The model includes two zones $\{A,B\}$. Zones A and B have an hourly energy market. Zone A can additionally implement a yearly capacity market.

Notations

$c \in C = \{A,B\}$	Electricity market zones
$k \in K$	Set of conventional generators
$j \in J$	Set of renewable generators
$t = (td,th)$	Time step (day, hour)
$g_{c,k,t}$	Energy generation (MWh)
$f_{c \to c',t}$	Exports from zone *c* to zone *c′* (MWh)
$d_{c,t}$	Energy served (MWh)
$ens_{c,t}$	Energy not served (MWh)
$cp_{c,k}$	Installed generation capacity (MW)
$cp_{c',k}^{CM,c}$	Capacity of generator *k* in zone *c′* participating in the capacity market of zone *c*. (MW)
$d_{c'}^{CM,c}$	Capacity procured in zone *c′* by the capacity market of zone *c* (MW)
$\lambda_{c,t}$	Energy market price (€/MWh)
$\lambda_{c'}^{CM,c}$	Capacity price in the capacity market of zone *c* for generators in zone *c′*. (€/MW)
$VOLL_c$	Maximum price on the energy market of zone *c*, or Value of Lost Load in zone *c* (€/MWh)
$\lambda_{MAX}^{CM,c}$	Maximum price of the capacity market of zone *c* (€/MW)
$D_{c,t}$	Reference energy demand (MWh)
$D_{c'}^{CM,c}$	Capacity demand in zone *c′* of the capacity market of zone *c* (MW)
$D_{c'+c'}^{CM,c}$	Total capacity demand for zones *c* and *c′* of the capacity market of zone *c* (MW)
IC	Interconnection capacity (MW)
MEC_c	Maximum Entry Capacity for foreign generators in the capacity market of zone *c* (MW)
$AF_{c,j,t}$	Renewable availability factor (%)
$V_{c,k}$	Generators' variable costs (€/MWh)
$I_{c,k}$	Generators' annualized investment costs (€/MW/y)
m	Capacity margin of the capacity market applied to increase security of supply (%)

2.2.1 Energy demand

In each zone *c*, the energy consumers' decisions are realized by one representative agent. For each hourly time step *t*, the agent decides on the consumption $d_{c,t}$ in order to maximize the consumers' surplus on the energy market. This surplus is proportional to the value of lost load $VOLL_c$ minus the energy price $\lambda_{c,t}$.[6] The national $VOLL_c$ are set at 3000€/MWh in both zones. The consumption $d_{c,t}$ is limited by the maximum reference demand $D_{c,t}$ (d.1). If generation resources are sufficient to cover the demand, $d_{c,t}$ will be maximum i.e. equal to the maximum reference demand $D_{c,t}$. When generating resources are not sufficient, the energy market clearing constraint will impose a reduction of the demand, i.e., energy not served $ens_{c,t} = D_{c,t} - d_{c,t}$.

$$\max_{d_{c,t}} \sum_{t \epsilon T} \left[(VOLL_c - \lambda_{c,t}) \, . \, (d_{c,t}) \right]$$

$$s.t.\ \forall c,t: \quad 0 \leq d_{c,t} \leq D_{c,t} \qquad (\beta_{c,t})\ \text{(d.1)}$$

Our time series are composed of 10 representative days (*td*) at regional level, whose respective weights (in day/year) are defined in Table 2. Each of the representative days is composed of 24 hourly time steps (*th*). For each zone, we build 4 representative daily profile categories (*Peak*, *High*, *Med*, and *Low*).[7] The 10 representative days consist of different combinations of profiles at the two-zones level, detailed in Table 2.

We build the representative profiles for zone A and zone B using historical electricity demand data from respectively, France and Germany, retrieved from the ENTSO-E transparency platform for the year 2019. We order the days by increasing daily average and classify them by category consistent with table 2 (e.g. the 40 first days are in the *Low* category). We then select each category's representative day based on the minimum distance with the category's average. For the *Peak* category, we make an exception and select as a representative the day with the highest daily average of the year. Finally, we multiply the profiles by an adjustment factor for each zone in order to achieve equivalent system's sizes.

Table 2 – Representative days, load profiles, and weights

td	1	2	3	4	5	6	7	8	9	10
Zone A	Peak	Peak	High	High	High	Med	Med	Med	Low	Low
Zone B	Peak	High	Peak	High	Med	High	Med	Low	Med	Low
Weight	1	9	9	82	11	11	180	22	22	18

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[6] We consider inelastic demand in the energy market. This aims to simplify the interpretation of the results, as studying the impact of consumers' behavior is not the focus of our assessment.

[7] Our aim is to compare between different market design configurations. The time series do not need to be fully representative of real-life examples. We, therefore, voluntarily use stylized time series. It allows us to easily explore the results, and to adjust the correlation between the zonal loads in our sensitivity analysis.

2.2.2 Conventional Generators

The investment and operation decisions of the conventional technology generator $k \epsilon K$ in zone c ϵ C are realized by one representative agent. The agent maximizes its profits considering the various market revenues available. The agent is a price-taker in both the energy and capacity markets.

$$\max_{g_{c,k,t}, cp_{c,k}, cp_{c,k}^{CM,c}, cp_{c,k}^{CM,c'}} \sum_{t \epsilon T} \left[(\lambda_{c,t} - V_{c,k}) \, . \, g_{c,k,t} \right] - I_{c,k} . cp_{c,k} + \lambda_c^{CM,c} \, . \, cp_{c,k}^{CM,c} + \lambda_c^{CM,c'} \, . \, cp_{c,k}^{CM,c}$$

$$s.t.$$

$$\forall t: \quad 0 \leq g_{c,k,t} \leq cp_{c,k} \quad (\mu_{c,k,t}) \quad \text{(g.1)}$$

$$0 \leq cp_{c,k}^{CM,c} \leq cp_{c,k} \quad (\mu_c^{CM,c}) \quad \text{(g.2a)}$$

$$0 \leq cp_{c,k}^{CM,c'} \leq cp_{c,k} \quad (\mu_c^{CM,c'}) \quad \text{(g.2b)}$$

In all scenarios, generators in zone can participate in an unflawed coupled energy market covering both zones. For each hourly time step, the agent operating technology *k* can decide on the energy generation $g_{c,k,t}$. Its net revenues from the energy market are determined by the energy market price $\lambda_{c,t}$ and unit variable costs $V_{c,k}$.The generation output $g_{c,k,t}$ is limited by the installed capacity $cp_{c,k}$ (g.1). On the annual reference time step, the agent can also decide on its installed capacity $cp_{c,k}$. The associated costs are determined by the annualized investment costs of the technology $I_{c,k}$.

The local zone *c* can additionally implement a capacity market (if it doesn't, $\lambda_c^{CM,c}$ is fixed at zero). The agent operating technology participates in the local capacity market with an amount of capacity $cp_{c,k}^{CM,c}$, limited by its installed capacity $cp_{c,k}$ (g.2a). It receives additional revenues from the capacity market proportional to the capacity price $\lambda_c^{CM,c}$. As the model considers no specific constraints on the conventional generators (we disregard unit commitment constraints such as ramping or minimum downtime), their de-rating factor for the capacity market is considered equal to one and not explicitly included in the model. The neighboring zone *c*' (ϵ *C\c*) can also implement a capacity market which allows for the explicit participation of generators in zone *c* through a dedicated bidding zone (if it doesn't, $\lambda_c^{CM,c'}$ is fixed at zero). Agent *k* in zone *c* participates in the foreign capacity market in *c'* with an amount of capacity $cp_{c,k}^{CM,c'}$, limited by its installed capacity $cp_{c,k}$ (g.2b). It can receive additional revenues proportional to the price of the capacity market of zone *c'* in bidding zone *c*, $\lambda_c^{CM,c'}$. In our model, only zone A can implement a capacity market, which can in some of our policy runs, allow for the explicit cross-border participation of generators in zone B.

Conventional generators are split into 3 stylized categories: *k* ϵ *{Base, Mid, Peak}*. Their variable and investment costs are defined in Table 2. The installed conventional capacity has a lower bound of zero, and there are no existing generators in the model (greenfield). The model defines the installed capacities in the long-term equilibrium. A slight asymmetry was introduced in the investment costs of both zones to avoid multiple equilibria.

Table 3 – Conventional generation parameters

Technology		**Base**	**Mid**	**Peak**
Variable costs (€/MWh)	$V_{c.k}$	36	53	76
Investment costs, Zone A (k€/MW.year)	$I_{A.k}$	180 + 1e-4	100	70 + 1e-4
Investment costs, Zone B (k€/MW.year)	$I_{B.k}$	180	100 + 1e-4	70

2.2.3 Renewable generators

We consider the installed renewable capacity as defined exogenously[8]. We therefore make the simple assumption that they do not participate in the capacity market. More precisely, the capacity market demand definition implicitly considers the renewable capacity. This is in line with a common practice in capacity markets, where renewable generators already receiving payments from renewable support schemes are opted-out of the mechanism, i.e. deduced from the demand and not allowed to participate.

The operating decision of the renewable generator $j \epsilon J$ in zone $c \epsilon C$ is realized by one representative agent. For each hourly time step , the agent can decide on the energy generation $g_{c,j,t}$ which is limited by the installed capacity $cp_{c,j}$ and technology availability factor $AF_{c,j,t}$ which are both exogenously defined. Its benefits are then determined by the energy market price $_{c,t}$. Its variable costs are assumed to be zero. The agent j,c maximizes its benefits from the energy market through one decision variables, $g_{c,j,t}$:

$$\max_{g_{c,j,t}} \sum_{t \epsilon T} \left[(\lambda_{c,j,t}) \ . \ g_{c,j,t} \right]$$

$$s.t.$$

$$\forall j,t: \qquad 0 \leq g_{c,j,t} \leq AF_{c,j} \ . \ cp_{c,j} \qquad (\mu_{c,j,t})$$

Renewable technologies are split into 2 technologies: $j \epsilon J = \{Wind, Solar\}$. The installed capacity of renewable technologies is set as follows $\forall j$, $cp_{A,j} = 20GW$, $cp_{B,j} = 24GW$. For each zone and technology, we build daily availability profiles $AF_{c,j,t}$. For a simpler interpretation of the results, we apply the same reference profiles for each representative day td (which varies depending on the hourly time step th). We build the representative profiles for zone A and zone B using historical renewable generation data from respectively, France and Germany, retrieved from the ENTSO-E transparency platform for the year 2019. We select as representative, the day with the minimum distance with the hourly average and daily average. For each technology, we then adjust the profiles in order to achieve the same average availability factors in both zones. The resulting average availability factor is 23.7% for wind and 13.5% for solar.

2.2.4 Capacity market demand

In a zone $c \epsilon C$ which has implemented a capacity market, the demand side of the market is operated by one unique agent.[9] Without explicit cross-border participation, the capacity market operator decides on the capacity demand $d_c^{CM,c}$ that maximizes the consumers' surplus in the local capacity market zone. This surplus is proportional to a reference maximum capacity price $\lambda_{MAX}^{CM,c}$ minus the actual capacity market price $\lambda_c^{CM,c}$[10]. The reference maximum capacity price is set arbitrarily high so it's not binding, at 1M€/MW. The capacity demand $d_c^{CM,c}$ is limited by the capacity target $D_c^{CM,c}$ (d.2).

$$\max_{d_c^{CM,c}} \ (\lambda_{MAX}^{CM,c} - \lambda_c^{CM,c}) \ . \ (d_c^{CM,c}) \ \ s.t.$$

$$\forall c,t: \qquad 0 \leq d_c^{CM,c} \leq D_c^{CM,c} \qquad (\beta_c^{CM,c}) \ \ \text{(d.2)}$$

---

[8] First, this is in line with the current market design set-up, as the main driver for renewable deployment in the EU is public support schemes auctioning long term contracts. Second, this allows to simplify and strengthen the comparability of results between different market design options. In practice, the roll-out of public two-way contracts for difference and private power purchase agreements might affect the energy price formation and therefore investment incentives. However, this is not the focus of our paper.

[9] This is equivalent to a centralized mechanism, as the consumers cannot directly interact with the capacity demand definition.

[10] We consider inelastic demand in the capacity market, to simplify the results' interpretation.

With explicit cross-border participation, the capacity market operator decides on the capacity demands in the local and foreign bidding zones, respectively $d_c^{CM,c}$ and $d_{c'}^{CM,c}$ to maximize the consumers' surplus. This surplus depends on the price of the capacity market in the local bidding zone $\lambda_c^{CM,c}$ and the foreign bidding zone $\lambda_{c'}^{CM,c}$. The capacity demand in the foreign bidding zone is limited by the foreign capacity target $D_c^{CM,c}$ (d.3) and the total capacity demand $d_c^{CM,c}$ and $d_{c'}^{CM,c}$ is limited by the total capacity target $D_{c+c'}^{CM,c}$ (d.4).

$$\max_{d_c^{CM,c},\, d_{c'}^{CM,c}} \left(\lambda_{MAX}^{CM,c} - \lambda_c^{CM,c}\right) . \left(d_c^{CM,c}\right) + \left(\lambda_{MAX}^{CM,c} - \lambda_{c'}^{CM,c}\right) . \left(d_{c'}^{CM,c}\right)$$

$$\text{s.t.}$$

$$0 \le d_{c'}^{CM,c} \le D_{c'}^{CM,c} \qquad \left(\beta_{c'}^{CM,c}\right) \text{ (d.3)}$$

$$0 \le d_c^{CM,c} + d_{c'}^{CM,c} \le D_{c+c'}^{CM,c} \qquad \left(\beta_{c+c'}^{CM,c}\right) \text{ (d.4)}$$

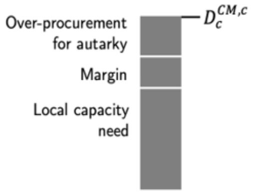
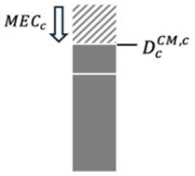
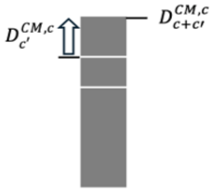
When zone *c* implements a capacity market, its reference conventional capacity target is noted $D^{CM,c,ref}$.We assume that the drivers for zone *c* to increase its Security of Supply are twofold. First, it initially aims at Security of Supply "autarky" or independence. The level of capacity required to reach this objective is measured through implementing a reference *National EOM* scenario. In this scenario, zone *c* has a perfectly competitive energy-only market, and is not interconnected to zone *c'*. The resulting installed conventional capacity is noted $(\sum_{k\epsilon K} [cp_{c,k}])_{National\ EOM}$. Second, zone *c* is very risk-averse to disconnections and implements an additional capacity margin of (expressed in %) for security. The resulting capacity target of the capacity market will be: $D^{cm,c,ref} = (\sum_{k\epsilon K} [cp_{c,k}])_{National\ EOM} \cdot (1 + m)$. The capacity margin is either varying, or set at 10% for reference in our results.

The Maximum Entry Capacity (MEC), abbreviated into the parameter MEC_c is used to quantify the contribution of resources in zone *c'* to the adequacy of zone *c*. The MEC should ideally represent the reduction of capacity induced in zone *c* resulting from the interconnection with zone *c'*. We, therefore, define the reference MEC_c^{ref} based on two theoretical reference scenarios: one in which zone *c* is isolated (*National EOM*), and one in which zone *c* is interconnected with zone *c'* (*Regional EOM*). In both, a perfectly competitive energy-only market is assumed, which allows to measure the optimal level of installed conventional capacity. MEC_C^{ref} is therefore defined as follows.

$$MEC_c^{ref} = \Big(\sum_{k\epsilon K}[cp_{c,k}]\Big)_{National\ EOM} \qquad - \Big(\sum_{k\epsilon K}[cp_{c,k}]\Big)_{Regional\ EOM}$$

With no cross-border participation, the demand is set to its reference $D^{cm,c,ref}$, which ignores imports' contribution to the security of supply. When implicit cross-border participation is implemented, the capacity target is reduced by the imports' contribution noted MEC_c. With explicit cross-border participation, the overall capacity target is raised again up to the reference $D^{CM,c,ref}$, an amount MEC_c of which can be procured abroad. If less capacity than the target of MEC_c is procured in the foreign bidding zone, more capacity will be procured in the local bidding zone. Table 4 summarizes the capacity demand considered with the various cross-border participation options.

Table 4 – Definition of the capacity market demands for the various cross-border participation rules

Capacity target	**No** **cross-border participation**	**Implicit** **cross-border participation**	**Explicit** **cross-border participation**
Total $D_{c+c'}^{CM,c}$	n.a.	n.a.	$D_c^{CM,c,ref}$
Local $D_c^{CM,c}$	$D^{CM,c,ref}$	$D_c^{CM,c,ref} - MEC_c$	n.a.
Foreign $D_{c'}^{CM,c}$	0	0	MEC_c
Stylized representation of the capacity market demand			

2.2.5 Interconnector

The interconnection between zone *A* and zone B is modeled by two agents, each operating in one direction. For each time step *t*, the agent operating in the *c→c'* direction maximizes the congestion revenues. It decides on the cross-border flow $f_{c\to c',t}$. It perceives congestion revenues, proportional to this flow and the energy price difference ($\lambda_{c',t} - \lambda_{c,t}$). The cross-border flow must be positive, and is limited to the interconnection capacity *IC* (I.1). In our results section, the interconnectivity is expressed in % relative to the approximate size of our zones (60GW): *interconnectivity=IC*$_{GW}$*/60*$_{GW}$. It is either varying or set at 10% (corresponding to a capacity *IC*=6GW) as a reference.

$$\max_{f_{c\to c',t}} \sum_{t\epsilon T} \left[(- \lambda_{c,t} + \lambda_{c',t}) \,.\, f_{c\to c',t} \right]$$

$$\forall c,t: \qquad 0 \le f_{c\to c',t} \le IC \qquad (\mu^{f}_{c\to c',t}) \text{ (I.1).}$$

In addition to the energy congestion revenues appearing in its maximization function, interconnectors' agents can earn capacity congestion revenues from explicit cross-border participation ($\lambda_c^{CM,c} - \lambda_{c'}^{CM,c}$). $d_{c'}^{CM,c}$ when it is implemented in the capacity market.

2.2.6 Market clearing

First is the energy market clearing. In zone *c*, for each hourly time step *t*. the total electricity supply must equal the total electricity demand. Electricity supply equals the sum of the conventional generation ($\sum_{k\epsilon K} [g_{c,k,t}]$), renewable generation ($\sum_{j\epsilon J} [g_{c,j,t}]$) and imports from the neighboring zone *c'* ($f_{c'\to c,t}$). Electricity demand equals the sum of the energy consumption ($d_{c,t}$) plus exports to the neighboring zone *c'* ($f_{c\to c',t}$).

$$\forall c,t: \qquad \sum_{k\epsilon K} [\, g_{c,k,t} \,] + \sum_{j\epsilon J} [\, g_{c,j,t} \,] + f_{c'\to c,t} - f_{c\to c',t} = d_{c,t} \qquad (\lambda_{c,t}) \text{ (c.1)}$$

Second is the capacity market clearing. Without explicit cross-border participation, the capacity contracted locally $\sum_{k\epsilon K} [cp_{c,k}^{CM,c}]$) must be equal to the capacity demand $d_c^{CM,c}$ (c.2). With explicit cross-border participation, the local market clearing constraint (c.2) holds. In addition, the total capacity contracted abroad $\sum_{k\epsilon K} [cp_{c',k}^{CM,c}]$) must be equal to the foreign capacity demand $d_{c'}^{CM,c}$ (c.3).

$$\sum_{k\epsilon K} \left[cp_{c,k}^{CM,c} \right] = d_c^{CM,c} \qquad (\lambda_c^{CM,c}) \text{ (c.2)}$$

$$\sum_{k\epsilon K} \left[cp_{c',k}^{CM,c} \right] = d_{c'}^{CM,c} \qquad (\lambda_{c'}^{CM,c}) \text{ (c.3)}$$

2.2.7 Local matching rule

Due to the symmetry of the national VOLL ($VOLL_A = VOLL_B$), the model can have multiple equilibria possible in case of simultaneous scarcity. We computed, ex-post, a reference unique equilibrium corresponding to *a local matching* rule. The rule is referred to as *local matching* because energy is served in priority where the generation is located. In other words, exports from zone *c* towards zone *c′* are not increased if this results in more unserved energy in zone *c*. The pseudo-code of the *local matching* rule implemented is the following:

```
For each time step t:
    For $c$ in $C$:
        $C' = C \setminus c$
        $\Delta f_{c\rightarrow c',t} = - min(ens_{c,t}, f_{c\rightarrow c',t})$
        $\Delta f_{c'\rightarrow c,t} = - min(ens_{c',t}, f_{c'\rightarrow c,t})$
        $f_{c\rightarrow c',t}^{new} = f_{c\rightarrow c',t} + \Delta f_{c\rightarrow c',t}$
        $ens_{c,t}^{new} = ens_{c,t} + \Delta f_{c\rightarrow c',t} - \Delta f_{c'\rightarrow c,t}$
        $d_{c,t}^{new} = d_{c,t} - \Delta f_{c\rightarrow c',t} + \Delta f_{c'\rightarrow c,t}$
    End
End
```

In Europe, the allocation of flows and unserved energy is eventually defined by the day-ahead market coupling algorithm, Euphemia. In case of concomitant scarcity, Euphemia applies by default a *curtailment-sharing* rule that aims to equalize as much as possible the curtailment ratios of the two zones. Member States are alternatively allowed to not share curtailment and to choose local matching, as we apply in this study. In practice, Member States might also be incentivized to restrict exports (when submitting the available transfer capacity) when reliability issues are anticipated in order to reduce their local energy not served in priority. We consider that *local matching* is, therefore, a likely scenario. This is also the approach assumed in Lambin & Léautier (2019). Selecting one rule or the other does not impact most of our results[11]. Note that the explicit cross-border participation into a capacity market does not directly interfere with the cross-border flow schedule defined in the wholesale market[12]. So, even if the capacity market of zone A procures generation capacity in zone B through explicit cross-border participation, that generation from zone B will not be allocated in priority to consumers in zone A if both zones are in scarcity.

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[11] As it only makes a difference during times of simultaneous scarcity, it does not affect the energy prices (equal to the VOLL), and the generation output (remains at maximum). As a result, generators' revenues and incentives are unaltered. The total consumers' costs are also unaltered, because they are indifferent to buying energy at a VOLL price, or having their energy not served at a VOLL cost . Congestion revenues are also unchanged because there is no price differential during simultaneous scarcity periods, the VOLL being reached in both zones. In our results section, changes would only materialize in section 3.1.3, which explores the change in energy not served.

[12] Article 26.4 of the Electricity Regulation: "*Cross-border participation in capacity mechanisms shall not change, alter or otherwise affect cross-zonal schedules or physical flows between Member States. Those schedules and flows shall be determined solely by the outcome of capacity allocation pursuant to Article 16* [General principles of capacity allocation and congestion management]"

3 Results and discussion

In this section, we present the results of our modelling simulations (introduced in section 2). We run our model in a configuration in which zone A implements a capacity market, and zone B implements no capacity mechanism. The capacity mechanism applies either no, implicit, or explicit cross-border participation.

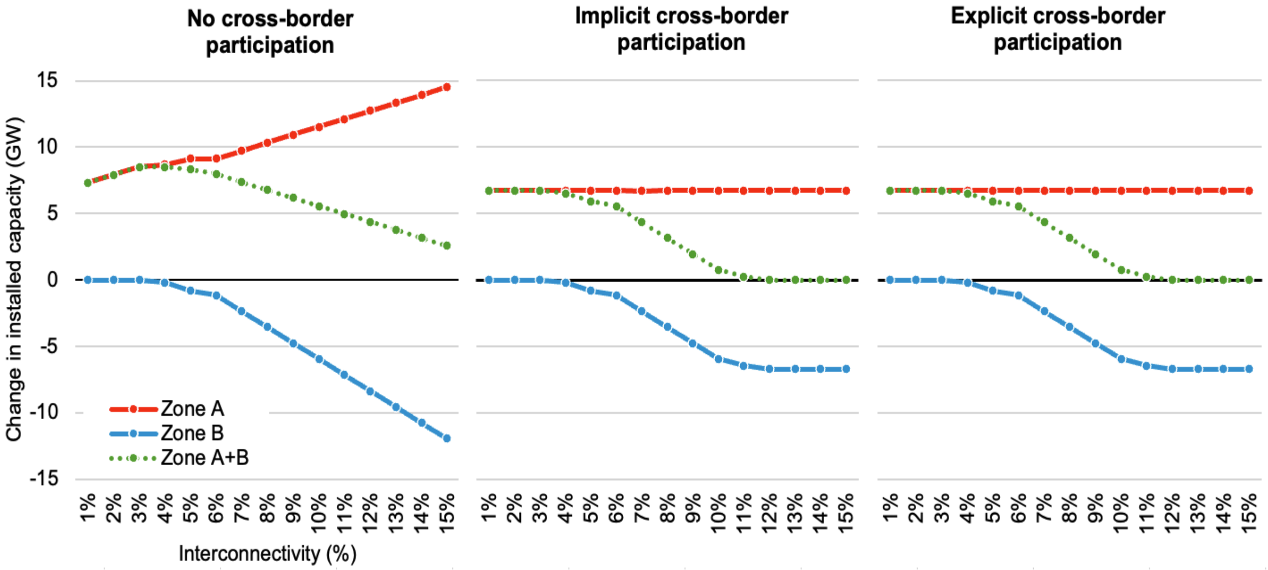
We assess the performance of the various cross-border participation rules in mitigating four cross-border effects related to the unilateral introduction of a capacity market: 1/ the displacement of neighboring generators capacity; 2/ the increase in total costs for neighboring consumers; 3/ the reduced security of supply in the neighboring zone; and 4/ the distortion of the interconnector's congestion rents.

3.1 Results

3.1.1 The displacement of neighboring generators capacity

In what follows, we first illustrate the generation capacity displacement from zone B without a capacity mechanism to zone A with a capacity market not applying cross-border participation. Second, we assess the effectiveness of applying implicit cross-border participation to address this externality. Third, we assess the effectiveness of applying explicit cross-border participation. We evaluate the change in generation capacity when zone A implements a capacity market, while zone B has no capacity mechanism. To understand the relative effect of the capacity market, we compute the change in installed capacity relative to the reference optimal energy-only scenario (Regional EOM scenario). The capacity market applies a fixed capacity margin of *m* = 10% (6.7GW). We compute the results for varying interconnectivity levels (expressed in %), in order to understand how interconnection capacity impacts the externalities.

Figure 1 - Change in installed generation capacity (Y axis, GW) relative to the reference optimal energy-only scenario, depending on the interconnectivity level (X axis, %), for various cross-border participation rules applied by the capacity market in zone A, and for a fixed capacity market margin (m=10%)



First, the issue of capacity displacement without cross-border participation (Figure 1, left graph). Increasing the installed generation capacity in zone A (red line) generally results in decreasing that installed in zone B (blue line). This is what we refer to as a displacement of capacity from zone B to zone A. This displacement is zero for lower levels of interconnectivity, and then increases with interconnectivity. Not accounting for imports results in an overshoot of the capacity needed in zone A increasing with the interconnectivity, which triggers more displacement of capacity from zone B.

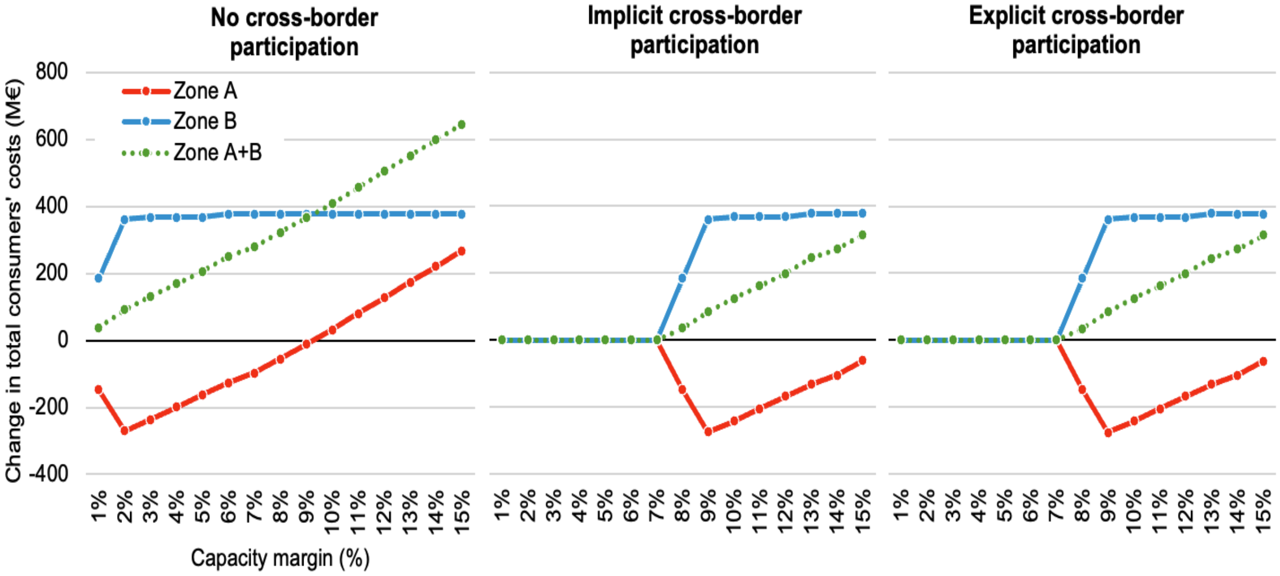
Second, the effectiveness of implicit cross-border participation (Figure 1, middle graph). As the capacity market now properly accounts for imports, it only adds in zone A an amount of generation capacity corresponding to the pre-defined margin (red line) of 6.7GW (10%). For lower to medium levels of interconnectivity, implicit cross-border participation does not reduce the displacement of capacity from zone B (blue lines are equal in the left and middle graphs). For higher levels of interconnectivity, the displacement of capacity from zone B is capped at -6.7GW. When this extreme is reached, all the capacity added in zone A has been displaced from zone B as the capacity change at the regional level is zero (green line). Implicit cross-border participation therefore limits the displacement effect by capping the creation of capacity in zone A to the pre-defined margin.

Third, the effectiveness of explicit cross-border participation (Figure 1, right graph). Surprisingly, explicit cross-border participation yields the same results as implicit cross-border participation. The capacity added in zone A (red line) is the same because the local capacity demand accounts for imports in both cases. With explicit cross-border participation, the generators in zone B can now get paid for their contribution to the capacity market of zone A. This additional revenue potential should intuitively result in more generation capacity for zone B (blue line), but this is not the case. This is because, in all scenarios and model computations, we find that the capacity price for generators in zone B participating in the capacity market of zone A is zero. The explanation is as follows: the energy market in zone B has an implicit demand for capacity. This implicit demand for capacity in zone B is much higher than the amount of capacity from zone B that can enter the capacity market in zone A. In other words, there will always be an oversupply of capacity from zone B to the capacity market zone A, which is why the price of that capacity is zero. As a result, the effects of explicit cross-border participation were already achieved with the simpler implicit cross-border participation rule.

3.1.2 The increase in costs for neighboring consumers

In what follows, we first show that implementing a capacity market without cross-border participation in zone A increases costs for the consumers in zone B. Second, we assess the effectiveness of implicit cross-border participation to address this effect. Third, we assess the effectiveness of explicit cross-border participation. We define consumers' costs as the sum of energy procurement costs, energy not served costs, and capacity procurement costs (only applies to consumers in zone A). We evaluate these costs when zone A implements a capacity market, while zone B has no capacity mechanism. To understand the relative effect of the capacity market, we compute the change in consumers' costs relative to the reference optimal energy-only scenario (*Regional EOM* scenario). The interconnectivity is fixed at 10% (*IC*=6 GW). We compute the change for a varying capacity margin *m* expressed in % (with 10% corresponding to 6.7GW) in order to identify an optimal choice for the capacity market operator.

Figure 2 - Change in the total consumers' costs (Y axis, M€) relative to the reference optimal energy-only scenario, depending on the capacity margin of the capacity market in zone A (X axis, %), and the cross-border participation rule applied, for a fixed interconnectivity level (10%)



First, the increased costs in zone B when zone A applies a capacity market without cross-border participation (Figure 2, left graph). The costs are systematically increased for consumers in zone B without any capacity mechanism (blue line). This increase is capped (+377M€) due to the limited interconnection capacity (10%). Surprisingly, the cost of implementing the capacity market can be negative for consumers in zone A (red line). If the objective of the capacity market operator is to minimize total consumers' costs it can do so by applying a capacity margin of 2%. Instead of free-riding the capacity market of zone A, consumers in zone B end up paying for it. The reason is, the capacity displacement makes consumers in zone B become more reliant on imports, for which they pay higher prices.[13] Only for high capacity margins the cost of implementing a capacity market is positive for the consumers in zone A.

Second, the effectiveness of implicit cross-border participation to mitigate the cost increase in zone B (Figure 2, middle graph). When implementing implicit cross-border participation, the capacity demand in zone A is limited to the capacity margin. This reduces the displacement of capacity discussed in the previous section and the resulting cost effects. If the capacity market applies a relatively low capacity margin, capacity is purely displaced from zone B to zone A, which does not come at an extra cost for the two zones (red, blue, and green lines at zero). If the capacity market operator aims to reduce costs for consumers in zone A (red line), it will be incentivized to increase the capacity margin. But for higher levels of capacity margins, the situation becomes equivalent to applying no cross-border participation.

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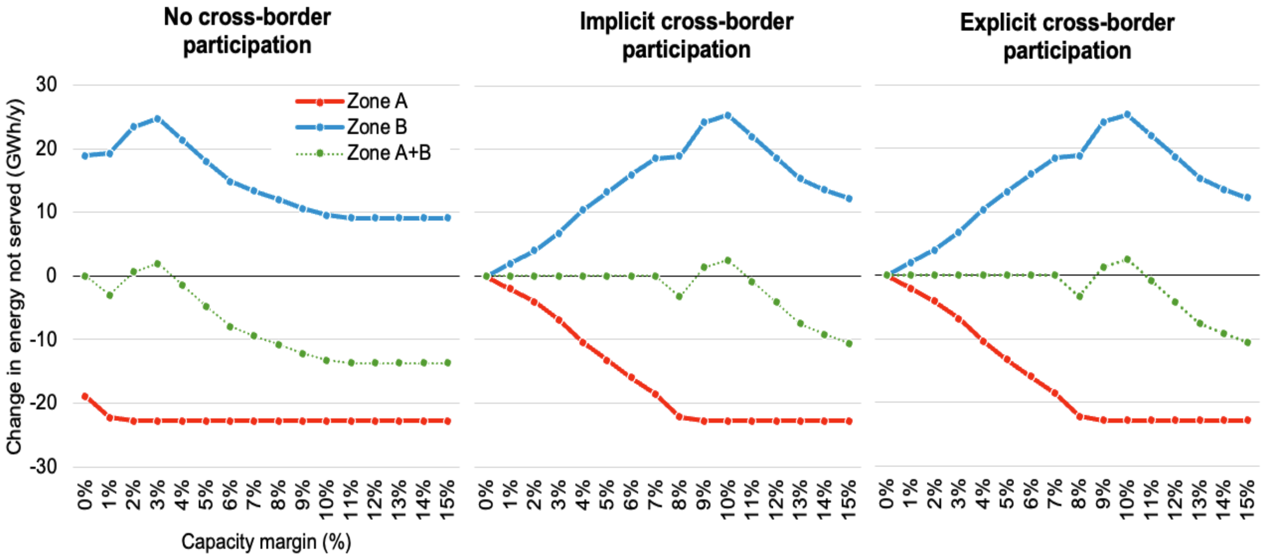
[13] For example, with a capacity margin of 3% and without cross-border participation, zone A benefits from a reduction of energy procurement costs, for both the electricity produced locally [-3650 M€] and imported [-344 M€], as well as a reduction of energy not served costs [-68 M€]. This more than compensates for the costs of procuring capacity in the capacity market [+3820 M€]. Consumers in zone B benefit from a reduction of local energy procurement costs because they procure less volume [-110 M€], which however translates in a consequent increase in import costs [+402 M€]. Due to less capacity installed locally, consumers in zone B moreover suffer from an increase in energy not served costs [+76 M€]. As a result, the total cost of the system increases [+124 M€], the costs for consumers in zone A decreases [-243 M€], so zone B end up paying for the total cost increase and the decrease of costs in zone A [+368 M€].

Third, the effectiveness of explicit cross-border participation to mitigate the cost increase in zone B (Figure 2, right graph).[14] Explicit cross-border participation does not mitigate the cost increase observed in zone B further than the simpler implicit rule. For the reasons explained in the previous section, both rules yield equal results.

3.1.3 The reduced security of supply in the neighboring zone

In this section, we first show that the introduction of a capacity market not applying cross-border participation in zone A leads to displacing energy not served towards zone B. Second, we assess the effectiveness of implicit cross-border participation to address this externality. Third, we assess the effectiveness of explicit cross-border participation to address this externality. We evaluate the volume of energy not served when zone A implements a capacity market, while zone B has no capacity mechanism. To understand the relative effect of the capacity market, we compute the change in energy not served relative to the reference optimal energy-only scenario (Regional EOM scenario). The interconnectivity is fixed at 10% (6 GW). We compute the change for a varying capacity margin *m* expressed in % (with 10% corresponding to 6.7GW) in order to identify optimal choices for the capacity market operator.

Figure 3 - Change in the volume of energy not served (Y axis, GWh/year), relative to the reference optimal energy-only scenario, depending on the capacity margin of the capacity market in zone A (X-axis, %), and the cross-border participation rule applied, for a fixed interconnectivity level (10%)



First, the displacement of energy is not served from zone A to zone B when zone A implements a capacity market without cross-border participation (Figure 3, left graph). Energy not served is systematically reduced in zone A (red line), in line with the capacity market's objective. The issue is that energy not served is increased in zone B (blue line). Without cross-border participation, the capacity demand in zone A is high enough to reduce energy not served close to zero in zone A (-23GWh). Therefore, adding more capacity in zone A through a higher capacity margin can reduce the energy not served displaced towards zone B (blue line is decreasing).

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[14] As discussed in 3.1.4, explicit cross-border participation can be implemented with or without recuperating capacity congestion rents for the interconnector. The results are plotted without. With the allocation of capacity congestion rents, the costs are only further increased in zone A.

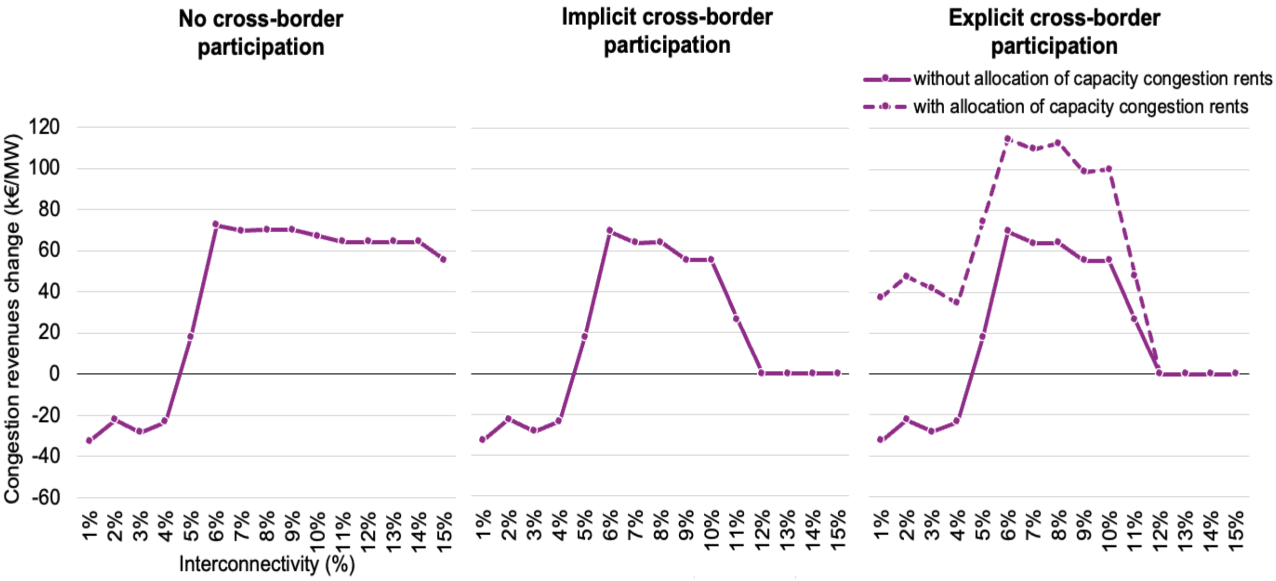
Second, the effectiveness of implicit cross-border participation to mitigate this externality (Figure 3, middle graph). For lower levels of capacity margin, energy not served is purely displaced from zone A (red line) towards zone B (blue line), as energy not served is unchanged at the regional level (green line). This displacement of energy not served, without any reduction at the regional level, questions the interest of introducing a capacity market unilaterally. For higher levels of capacity margin, the situation becomes equivalent to what we observed without cross-border participation. We moreover observe that implementing implicit cross-border participation limits the performance of the capacity market in reducing the energy not served in zone A, which is its objective. If the capacity market is implemented with a target expressed in energy not served reduction, it will select a different capacity margin with or without cross-border participation. In turn, the effect on the energy not served of zone B will be equal whatever rule is applied.

Third, the effectiveness of explicit cross-border participation to mitigate this externality (Figure 3, right graph). For the same reasons as in the previous sections, explicit cross-border participation performs equally as the simpler implicit rule.

3.1.4 The distortion of congestion rents

In what follows, we first show that introducing a capacity market in zone A affects the congestion revenues of the interconnector between zone A and zone B. Second, we assess the effectiveness of implicit cross-border participation to address this externality. Third, we assess the effectiveness of explicit cross-border participation to address this externality with two implementation options. To understand the relative effect of the capacity market, we compute the change in total congestion revenues relative to the reference optimal energy-only scenario (*Regional EOM* scenario). The capacity market margin is fixed at 10% (6.7GW). We compute the change for a varying interconnectivity level expressed in % (with 10% corresponding to 6GW) in order to understand how this impacts the change in congestion revenues. Revenue change is adjusted by the interconnection capacity to obtain a value in k€/MW.

Figure 4 - Change in the total congestion rents for interconnectors (Y axis, k€/MW), relative to the reference optimal energy-only scenario, depending on the interconnectivity level (X-axis, %), and the various cross-border participation rules, for a fixed capacity market margin (m=10%)



First, the distortion of congestion rents without cross-border participation (Figure 4, left graph). We observe that congestion rents can be either reduced or increased. It all depends on the parameters. For lower levels of interconnectivity, the capacity market in zone A reduces congestion rents. The prevailing effect is a reduction of imports into zone A, which has more capacity available locally. For higher levels of interconnectivity, the capacity market in zone A increases congestion rents. The prevailing effect is an increase in exports towards zone B, explained by a large displacement of generation capacity from zone B to zone A.

Second, the effectiveness of implicit cross-border participation to remedy this distortion (Figure 4, middle graph). For lower levels of interconnectivity, implementing implicit cross-border participation has almost no effect on the congestion rents (left and middle graphs are equivalent). For high levels of interconnectivity, implicit cross-border participation appears to fully mitigate the distortion of congestion rents as they reach zero. But this is only because the interconnector is oversized; the congestion rents are zero both with and without the capacity market.

Third, the effectiveness of explicit cross-border participation to remedy this distortion (Figure 4, right graph). The effectiveness of explicit cross-border participation depends on the two implementation options that we introduce in Figure 4 (described in section 2.1). With the first option, no congestion revenues are allocated to the interconnector, and explicit and implicit cross-border participation are equivalent. With the second option, congestion revenues are allocated to the interconnector, and explicit cross-border participation naturally increases its revenues. Overall, explicit cross-border participation does not address the issue, as positive or negative distortions are systematically observed. Note that a positive distortion of congestion rents can eventually impact the level of interconnectivity. As the capacity displacement increases with interconnectivity, this could trigger a snowball effect.

3.2 Discussion and model limitations

In what follows, we first examine the sensitivity of our results to the modeling parameters used. Second, we discuss whether our results can be generalized to the case in which capacity markets are needed to correct the imperfections of the energy-only market. Third, we evaluate whether our results hold if the evolution of imports' availability is accounted for in the capacity market's parameters. Fourth we assess the applicability of our results to the case in which the neighboring zone also has implemented a capacity market. Finally, we try to explain why the first experiences with explicit cross-border participation in practice are different from what we would expect based on our modeling exercise.

First, how sensitive are our results to the model parameters used? We will reflect mainly on the capacity displacement effect (section 3.1.1), as the other externalities are largely a consequence of it. One critical parameter appears to be the correlation between the two zones' demands. In our results section, we have assumed one simultaneous peak day. This might limit the complementarity of the two zones and the interest of cross-border participation. However, the peak hours do not materialize at the same time, and a positive MEC confirms that both zones do rely on each other for adequacy. In addition, we plotted in Appendix II.i the capacity displacement with no simultaneous peak day, which confirms our conclusions. Another critical parameter is the capacity margin, which is assumed relatively high (10%) in Figure 1. We, therefore, provide in Appendix II.ii a sensitivity analysis of the capacity margin, which confirms and extends the observations made in section 3.1.1.

Second, can our results be generalized to the case with an imperfect energy-only market? In Appendix II.iii, we provide simulation results for an energy-only market with missing money due to a price cap below the consumers' VOLL. The capacity market in zone A is implemented to restore the optimal level of capacity. The same conclusions as described in our results section hold. Unless interconnectivity is low, we observe a pure displacement of capacity from zone B to zone A, and of energy not served from zone A to zone B. Cross-border participation (both implicit and explicit) does not properly mitigate the displacement effect. In a well-interconnected system, implementing capacity markets at the national level therefore only appears to displace the problem from one zone to the other. This is problematic for zone B suffering from the capacity displacement and its effects, but also problematic for zone A. While its capacity market restores the capacity level to optimal, it does not restore the energy not served to optimal. Indeed, because capacity is displaced and not created, zone A can rely on more local resources but on less neighboring resources. Zone A, despite implementing a capacity market, only partly restores its own security of supply due to the cross-border effects exerted on zone B.[15]

Third, what if we account for the evolution of imports' availability in the capacity market's parameters? For simplicity, we have relied on an ideal capacity target which is fixed "ex-ante". In practice, the capacity demand would not be fixed but adjusted iteratively[16]. On the one hand, the finding made in the previous paragraph would be nuanced. If zone A iteratively defines its optimal capacity needs considering zone B's past reactions, it should be able to ensure security of supply. On the other hand, the externalities exerted in zone B would be magnified. We established that when implementing its capacity market, zone A indirectly reduces the availability of imports from zone B during scarcity. In turn, the MEC should decrease, meaning that the local capacity demand in zone A would increase. As a result, the capacity displacement and related effects would only be reinforced. In all figures, we expect the results of an iterative approach to range between No and implicit/explicit cross-border participation.

Fourth, can explicit cross-border participation become relevant when the neighboring zone also has a capacity market? In such a configuration, explicit cross-border participation can produce a non-zero price for capacity in the neighboring zone. However, the regulatory objective would be different. The regulatory challenge is to coordinate between two (competing) capacity markets rather than to fix the externalities of a capacity market on the neighboring zone. If both zones have a capacity market, explicit cross-border participation results in important complexities for market participants because it implies multiplying prices and auctions. If all European countries had a capacity market allowing explicit cross-border participation from their neighbors, there would be at least 129[17] different prices for capacity. Today, complexity also results from the non-harmonization of mechanisms (type and length of contracts, penalty rules, de-rating factors…), and the sequence of auctions. In the presence of uncertainty, having to select explicitly which national capacity market(s) to participate in is likely to result in inefficient bidding. Implicit cross-border participation removes this complexity but might also not be satisfactory. With both implicit and explicit, there is no direct link between what the two capacity mechanisms effectively procure, and therefore no co-optimization during procurement.

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[15] To restore its energy not served to optimal, zone A needs to either apply a high capacity margin, remove cross-border participation, or keep a low interconnectivity.

[16] The optimal capacity demand for zone A can be computed by considering an unflawed energy-only market where the installed capacity in zone B is exogenously set as in the last iteration result, rather than endogenously set.

[17] The calculation is based on information about interconnection from the TYNDP (ENTSO-S, 2022). We don't account for intra-country bidding zones such as in Italy, which would increase even more this number.

Fifth, what might explain the difference between the first experiences we have with explicit cross-border participation and our results? ACER (2023) refers to the very limited experience we have so far with explicit cross-border participation in the capacity markets of Italy and Poland. Based on our work and the academic work we referred to in this paper, we would expect the supply of capacity from a neighboring zone to be higher than the amount of capacity that can be imported. We could also expect the price for that capacity to be zero. However, generators in Montenegro participated in the Italian capacity market at a price of 25,075€/MW (for the delivery year 2024). Moreover, the Polish capacity market allowed the participation of Swedish capacity for up to 339 MW (delivery year 2027), but no capacity was procured in the Swedish zone. This might be explained by the limited experience with explicit cross-border participation, as well as the high transaction costs or other factors discouraging participation, such as the presence of penalties and payback clauses, or a burdensome qualification process. In other words, we expect the price to go towards zero as it will become easier for neighboring capacity to participate in the national capacity markets. It also implies that countries with a capacity market have an incentive to make it easier for non-domestic resources to participate in their market.

4. Conclusion

In the results section, we provided a detailed description of four cross-border effects resulting from the unilateral introduction of a capacity market on a neighboring zone without any capacity mechanism (or energy-only zone). We showed that generation capacity is displaced from the energy-only to the capacity market zone. This eventually reduces the security of supply in the energy-only zone, as unserved energy is displaced from the capacity market to the energy-only zone. These effects also result in an unfair cost distribution. The cost of the capacity market can be negative to local consumers, and indirectly borne by the neighboring energy-only consumers. Finally, the introduction of a capacity market can affect the interconnector's congestion revenues either positively or negatively.

This provided us with three main findings on cross-border participation. Our first finding is that cross-border participation rules do mitigate the externalities of a capacity market, but not fully. Accounting for the contribution of neighboring capacities allows to avoid overshooting the capacity demand. It limits the capacity displacement effect, and consequential effects on costs and unserved energy, but does not fully mitigate them. Our second finding is that the performance of explicit and implicit cross-border participation is equivalent. The reason is, with explicit participation, the capacity price perceived by generators in the energy-only zone tends towards zero. A difference between explicit and implicit cross-border participation materializes when capacity congestion rents are recuperated by the capacity market operator. The increase in congestion rents does not, however, mitigate the other cross-border effects. Our third finding is that a capacity market applying cross-border participation without any additional margin might fail to achieve its very objective, ensuring security of supply, unless interconnectivity is kept low. The reason is that it only displaces capacity from the neighboring zone. As a result, while the capacity market zone can rely on more local resources during scarcity, it can also rely on fewer imports.

These findings lead us to two main conclusions. Based on the first and the third findings, we conclude that cross-border participation appears to be a false hope for fixing capacity market externalities that affect the neighboring energy-only zones. In the medium term, we might need to evolve towards a more European approach to effectively ensure security of supply and avoid cross-border effects. Whether having harmonized national capacity markets is enough, or whether we need more coordination (or integration) of capacity markets, is the next question to address in this research. In any case, the more capacity markets are introduced, the more countries without a capacity mechanism are incentivized to introduce one. If they do not, they might end up paying for the capacity market of their neighbors, or they might be incentivized to limit the level of interconnectivity with their neighbors. Based on the second finding, we have a shorter-term conclusion for the objective of the latest electricity market reform to streamline the implementation of capacity mechanisms at the national level. If the main objective of cross-border participation is to mitigate cross-border effects of capacity markets on energy-only zones, then we could consider moving from explicit to implicit cross-border participation as the latter is simpler and equally efficient.

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Appendix

I Model description

Conventional generators

Market design in zone *c*	Explicit cross-border participation into zone *c'*	Optimisation function of agent in zone *c*	MCP formulation
EOM	No	$\max_{g_{c,k,t},cp_{c,k},} \sum_{t\in T}\left[\left(\lambda_{c,t} - V_{c,k}\right).\ g_{c,k,t}\right] - I_{c,k}.cp_{c,k}$ s.t. $\forall k,t:\ \ (0 \leq)\ g_{c,k,t} \leq cp_{c,k}\ \ \ \left(\mu_{c,k,t}\right)$ (g.1)	$-\lambda_{c,t} + V_{c,k} + \mu_{c,k,t} \geq 0\ \ \perp\ \ g_{c,k,t} \geq 0$ (1.1) $-\sum_{t\in T}\left[\mu_{c,k,t}\right] + I_{c,k} \geq 0\ \ \perp\ cp_{c,k} \geq 0$ (1.2) $cp_{c,k} - g_{c,k,t} \geq 0\ \ \perp\ \ \mu_{c,k,t} \geq 0$ (1.3)
EOM	Yes	$\max_{g_{c,k,t},cp_{c,k},cp_{c,k}^{CM,c'}} \sum_{t\in T}\left[\left(\lambda_{c,t} - V_{c,k}\right).\ g_{c,k,t}\right]$ $- I_{c,k}.cp_{c,k}$ $+ \lambda_c^{CM,c'}\ .\ cp_{c,k}^{CM,c'}$ s.t. (g.1), and $\forall k:\ \ \ (0 \leq)\ cp_{c,k}^{CM,c'} \leq cp_{c,k}\ \ \left(\mu_{c,k}^{CM,c'}\right)$ (g.2b)	(1.1)(1.3) and $-\sum_{t\in T}\left[\mu_{c,k,t}\right] + I_{c,k} - \mu_{c,k}^{CM,c'} \geq 0\ \perp cp_{c,k} \geq 0$ (1.2b) $-\lambda_c^{CM,c'} + \mu_{c,k}^{CM,c'} \geq 0\ \ \perp\ \ cp_{c,k}^{CM,c'} \geq 0$ (1.4b) $cp_{c,k} - cp_{c,k}^{CM,c'} \geq 0\ \perp\ \mu_{c,k}^{CM,c'} \geq 0$ (1.5b)
CM	No	$\max_{g_{c,k,t},cp_{c,k},cp_{c,k}^{CM,c}} \sum_{t\in T}\left[\left(\lambda_{c,t} - V_{c,k}\right).\ g_{c,k,t}\right]$ $- I_{c,k}.cp_{c,k}$ $+ \lambda_c^{CM,c}\ .\ cp_{c,k}^{CM,c}$ s.t. (g.1) $c,k:\ \ \ (0 \leq)\ cp_{c,k}^{CM,c}\ \leq cp_{c,k}\ \ \ \left(\mu_{c,k}^{CM,c}\right)$ (g.2a)	(1.1)(1.3) and $-\sum_{t\in T}\left[\mu_{c,k,t}\right] + I_{c,k} - \mu_{c,k}^{CM,c'} \geq 0\ \perp cp_{c,k} \geq 0$ (1.2b) $-\lambda_c^{CM,c'} + \mu_{c,k}^{CM,c'} \geq 0\ \ \perp\ \ cp_{c,k}^{CM,c'} \geq 0$ (1.4b) $cp_{c,k} - cp_{c,k}^{CM,c'} \geq 0\ \perp\ \mu_{c,k}^{CM,c'} \geq 0$ (1.5b)

Renewable generators

Market design in zone *c*	Optimization function of agent in zone *c*	MCP formulation
All	$\max_{g_{c,j,t},} \sum_{t\in T}\left[\left(\lambda_{c,j,t}\right).\ g_{c,j,t}\right]$ s. t. $\forall j,t:\ \ \ (0 \leq)\ g_{c,j,t} \leq AF_{c,j}.cp_{c,j}\ \ \ \left(\mu_{c,j,t}\right)$	$-\lambda_{c,t} + \mu_{c,j,t} \geq 0\ \ \perp\ \ g_{c,j,t} \geq 0$ (2.1) $AF_{c,j}.cp_{c,j} - g_{c,j,t} \geq 0\ \ \perp\ \ \mu_{c,j,t} \geq 0$ (2.2)

Market operators

Market of zone *c*	Explicit cross-border participation	Optimization function of the market operator in zone *c*	MCP formulation
Hourly energy market	N.a.	$\max_{g_{c,k,t},cp_{c,k},} \sum_{t\in T}\left[\left(\lambda_{c,t} - V_{c,k}\right).\ g_{c,k,t}\right] - I_{c,k}.cp_{c,k}$ s.t. $\forall k,t:\ \ (0 \leq)\ g_{c,k,t} \leq cp_{c,k}\ \ \ \left(\mu_{c,k,t}\right)$ (g.1)	$-VOLL + \lambda_{c,t} + \beta_{c,t} \geq 0\ \ \perp\ \ d_{c,t} \geq 0$ (3.1) $D_{c,t} - d_{c,t} \geq 0\ \ \perp\ \ \beta_{c,t} \geq 0$ (3.2)
Yearly capacity market	No	$\max_{d_c^{CM,c}}\left(\lambda_{MAX}^{CM,c} - \lambda_c^{CM,c}\right).\left(d_c^{CM,c}\right)$ s.t. $\forall c,t:\ \ \ (0 \leq)d_c^{CM,c} \leq D_c^{CM,c}\ \ \ \ \left(\beta_c^{CM,c}\right)$	$-\lambda_{MAX}^{CM,c} + \lambda_c^{CM,c} + \beta_c^{CM,c} \geq 0 \perp\ d_c^{CM,c} \geq 0$ (3.3) $D_c^{CM,c} - d_c^{CM,c} \geq 0\ \ \perp\ \ \beta_c^{CM,c} \geq 0$ (3.4)
	Yes	$\max_{d_c^{CM,c},d_{c'}^{CM,c}}\left(\lambda_{MAX}^{CM,c} - \lambda_c^{CM,c}\right).\left(d_c^{CM,c}\right)$ $+\left(\lambda_{MAX}^{CM,c} - \lambda_{c'}^{CM,c}\right).\left(d_{c'}^{CM,c}\right)$ s.t. $(0 \leq)d_{c'}^{CM,c} \leq D_{c'}^{CM,c}\ \ \ \ \left(\beta_{c'}^{CM,c}\right)$ With $D_{c'}^{CM,c} = MEC^c$ $d_c^{CM,c} + d_{c'}^{CM,c} \leq D_{c+c'}^{CM,c}\ \ \ \left(\beta_{c+c'}^{CM,c}\right)$	$-\lambda_{MAX}^{CM,c} + \lambda_c^{CM,c} + \beta_{c+c'}^{CM,c}\ \ \perp\ d_c^{CM,c} \geq 0$ (3.3b) $-\lambda_{MAX}^{CM,c} + \lambda_{c'}^{CM,c} + \beta_{c'}^{CM,c} + \beta_{c+c'}^{CM,c}\ \ \perp\ d_{c'}^{CM,c} \geq 0$ (3.3c) $D_{c'}^{CM,c} - d_{c'}^{CM,c} \geq 0\ \ \ \perp\ \beta_{c'}^{CM,c} \geq 0$ (3.4b) $D_{c+c'}^{CM,c} - d_c^{CM,c} - d_{c'}^{CM,c} \geq 0\ \ \ \perp\ \beta_{c+c'}^{CM,c} \geq 0$ (3.4c)

Interconnector			
IC definition	**Explicit cross-border participation into zone *c′***	**Agent (*c* → *c′*) optimization function**	**MCP formulation**
Exogenous	No	$\max_{f_{c\to c',t}} \sum_{t\in T}[(-\lambda_{c,t} + \lambda_{c',t}) \cdot f_{c\to c',t}]$ $\forall c,t: \quad (0 \leq) f_{c\to c',t} \leq IC \qquad (\mu^{f}_{c\to c',t})$	$\lambda_{c,t} - \lambda_{c',t} + \mu^{f}_{c\to c',t} \geq 0 \quad \perp \quad f_{c\to c',t} \geq 0 \quad (4.1)$ $IC - f_{c\to c',t} \geq 0 \quad \perp \quad \mu^{f}_{c\to c',t} \geq 0 \quad (4.2)$

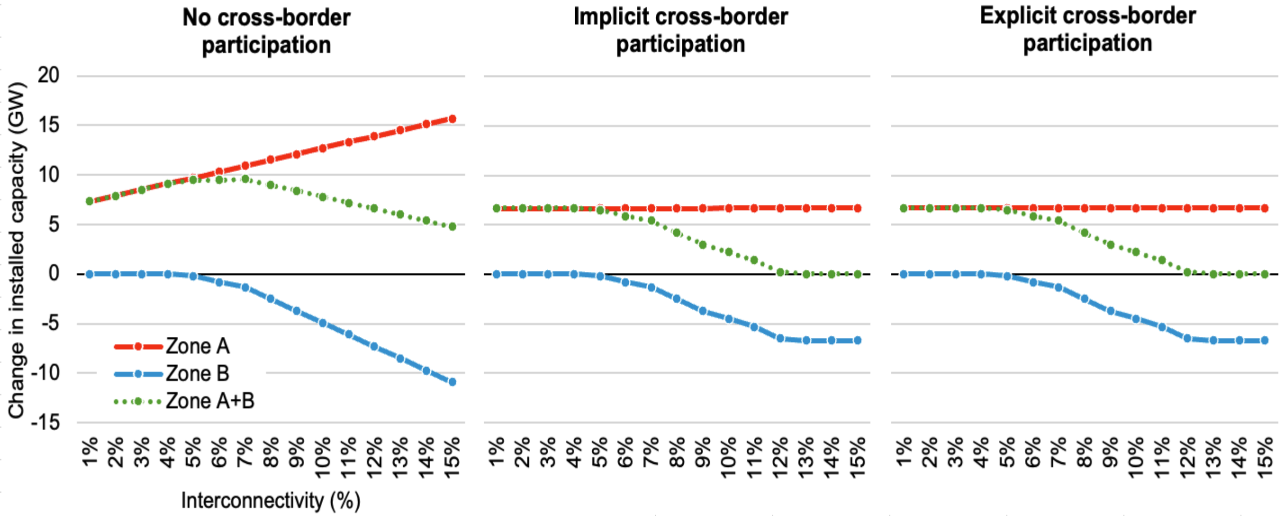
Market clearing		
Market of zone *c*	**Cross-border participation**	**Constraint**
Hourly energy market	N.a.	$\forall t: \quad \sum_{k\in K}[g_{c,k,t}] + \sum_{j\in J}[g_{c,j,t}] + f_{c'\to c,t} - f_{c\to c',t} = d_{c,t} \qquad (\lambda_{c,t})$
Capacity market	No	$\sum_{k\in K}[cp^{CM,c}_{c,k}] = d^{CM,c}_{c} \qquad (\lambda^{CM,c}_{c})$
	Yes	$\sum_{k\in K}[cp^{CM,c}_{c,k}] = d^{CM,c}_{c} \qquad (\lambda^{CM,c}_{c})$ $\sum_{k\in K}[cp^{CM,c}_{c',k}] = d^{CM,c}_{c'} \qquad (\lambda^{CM,c}_{c'})$

II Sensitivity analysis

II.i Capacity displacement with non-simultaneous peak days

In our results section, we have assumed that simultaneous peak days occur once per year. In Figure 5, we compute a sensitivity analysis of the results shown in Figure 1 when there is no simultaneous peak day (the weight of the day td=1 is set to zero).

Figure 5 - Change in installed capacity (Y axis, GW) relative to the reference optimal energy-only scenario, depending on the interconnectivity level (X-axis, %), and the cross-border participation rule applied, for a fixed capacity margin (m=10%), when peak days never occur simultaneously in zone A and zone B

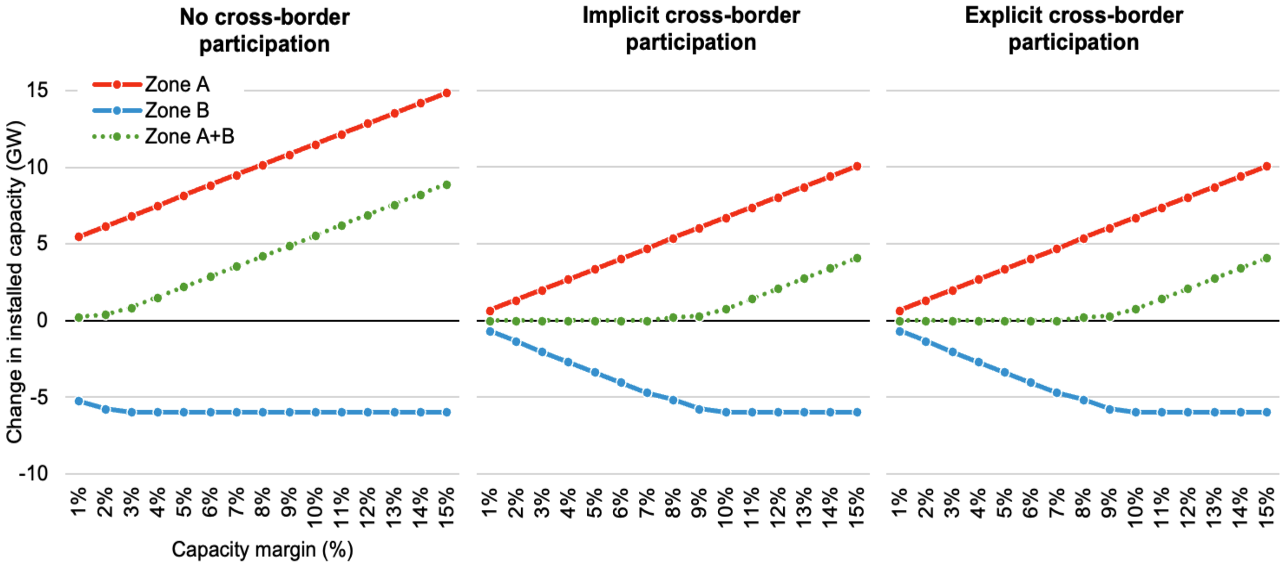


We observe that the maximum entry capacity (MEC) increases, as expected, because having no simultaneous peak days allows for more complementarity between the systems. Our conclusions from section 3.1.1 still hold. Implicit and explicit cross-border participation perform equally because the price of capacity in the foreign bidding zone B remains zero. Moreover, a full capacity displacement is observed for high interconnectivity levels.

II.ii Capacity displacement for varying capacity margin

In section 3.1.1, Figure 1, we have assumed that the capacity market in zone A has a fixed and high capacity margin (10%, 6.7GW). In Figure 6, we compute a sensitivity analysis of our results with a varying capacity margin. The interconnection capacity is fixed (at 10%, 6GW).

Figure 6 - Change in installed generation capacity (Y axis, GW) relative to the reference optimal energy-only scenario, depending on the capacity margin of the capacity market in zone A (X-axis, %), for various cross-border participation rules applied by the capacity market in zone A, and for a fixed interconnectivity (10%, 6GW)



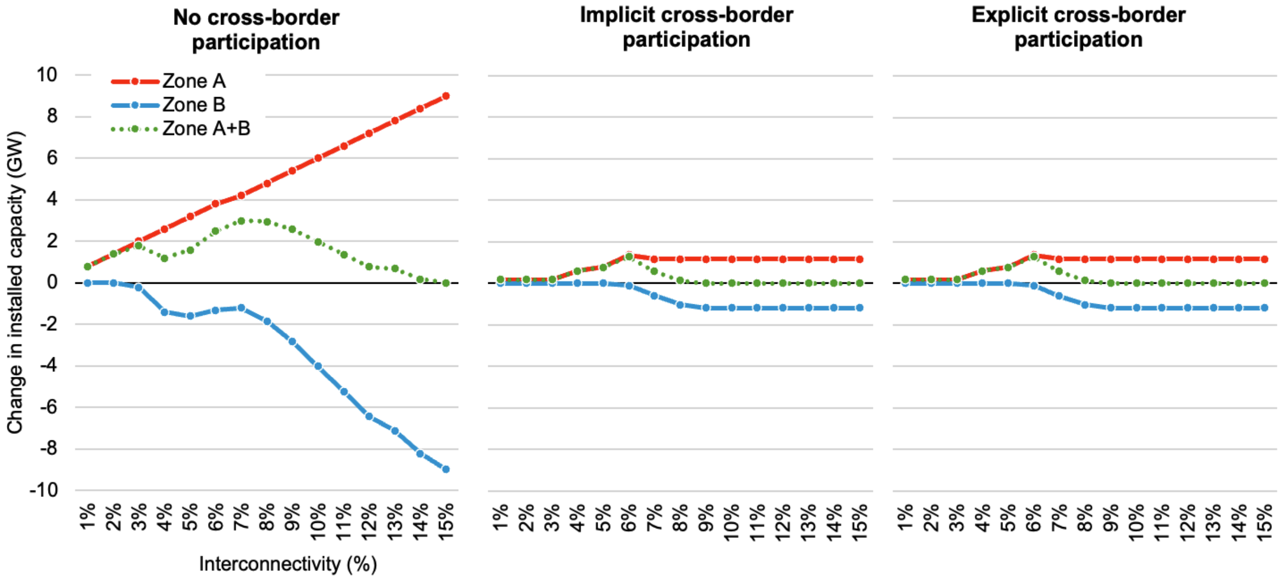
Our conclusions still hold. For a small capacity demand (relative to the interconnectivity), the capacity market only displaces capacity from zone B to zone A, as there is no capacity creation at the regional level. When the capacity demand is higher, the capacity displacement is limited by the interconnection capacity, and there is capacity creation at the regional level. Explicit and implicit cross-border participation perform equally in limiting the capacity displacement effect. They perform better than no cross-border participation because they limit the local capacity demand in zone A to the capacity margin.

II.iii Capacity and energy not served displacement with a capacity market used to restore the optimal capacity level when the energy market is price-capped

In our results section, we have assumed a perfect energy market. Therefore, the capacity market increases the capacity and reliability level of zone A above optimal, which might magnify the cross-border externalities observed. In this section, we instead assume that the energy market is flawed by a price cap. In this section, we first discuss our modelling approach, second the displacement of capacity, third the displacement of energy not served, and fourth the effectiveness of explicit cross-border participation.

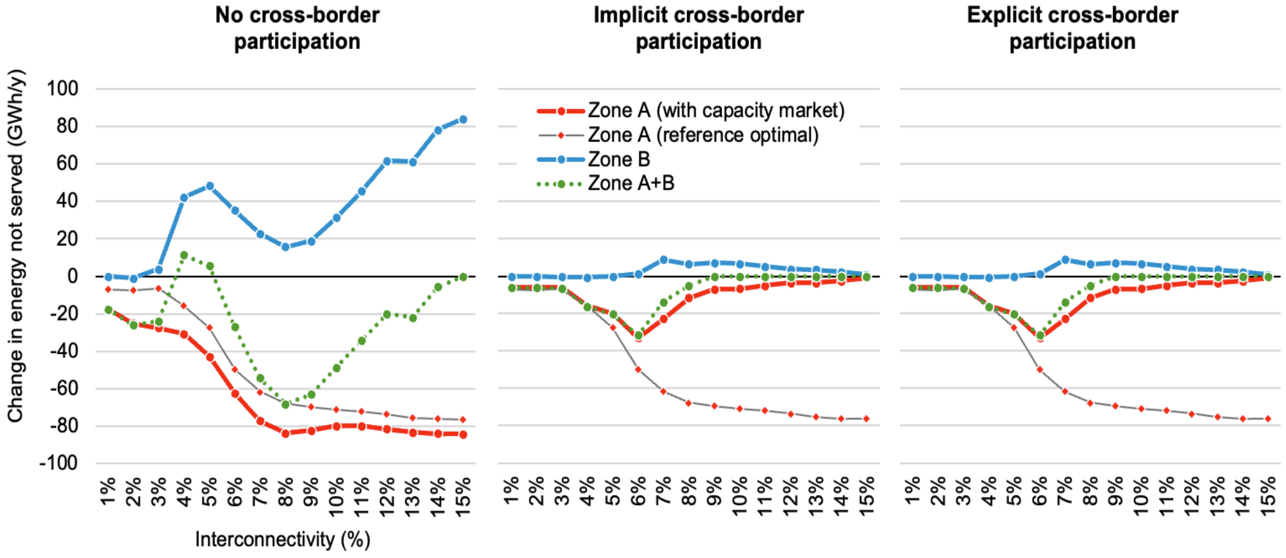
First, our modelling approach. We first run the model for a perfect energy-only scenario. Then, we introduce a price cap, through a new constraint on the wholesale energy market price (with PC=2000€/MWh), which results in missing money for generators and, thereby, a reduction of the installed capacity. Finally, zone A introduces a capacity market, while zone B does not. The capacity market in zone A aims to restore the optimal capacity computed in the perfect energy-only scenario. The energy market remains imperfect, due to the price cap, in both zones.

Figure 7 - Change in installed generation capacity (Y axis, GW) relative to the imperfect energy-only scenario, depending on the interconnectivity level (X axis, %), and for various cross-border participation rule applied by the capacity market in zone A



Second, the displacement of capacity. In Figure 7 we plotted the change in installed generation capacity in both zones following the introduction of the capacity market in zone A, compared to the initial situation with an imperfect energy-only market. Not applying cross-border participation results in an overshoot in the capacity demand increasing with the interconnectivity level, which also translates into an increasing capacity displacement from zone B to zone A. With cross-border participation, the capacity demand in zone A corresponds to the theoretical optimal (computed based on a reference perfect energy-only scenario) and is relatively small. As a result, the capacity displacement is much more limited.

Figure 8 - Change in energy not served (Y axis, GWh/y) relative to the imperfect energy-only scenario, depending on the interconnectivity level (X axis, %), and the cross-border participation rule applied.



Third, the displacement of energy not served. In figure 8, we plotted the change in energy not served compared to the initial imperfect energy-only scenario. In zone B, energy not served is either unchanged or increased. It is slightly increased for medium interconnectivity levels with cross-border participation (middle and right graphs), and highly increased when the capacity market does not apply cross-border participation (left graph). The objective of the capacity market in zone A is to reduce its energy not served to the optimal (plotted as a reference in grey lines). For medium to high levels of interconnectivity, surprisingly, the capacity market applying cross-border participation fails to reach this objective. In other words, restoring the optimal local capacity level does not mean restoring the optimal security of supply level. Because it is displacing capacity from zone B, zone A can count on more local generators, but also on fewer neighboring generators. The only solution for zone A to restore its adequacy is to overshoot its capacity demand (by not applying cross-border participation or by applying a positive capacity margin), or to keep interconnectivity low.

Fourth, the effectiveness of explicit cross-border participation in mitigating these effects. Explicit and implicit cross-border participation perform equally in mitigating the capacity displacement and energy not served displacement effects. They perform well for lower levels of interconnectivity, as the capacity reduction in zone B is zero, and energy not served is effectively restored close to its optimal level. However, for higher levels of interconnectivity, they both fail to mitigate the capacity displacement effect. Capacity is purely displaced from zone B to zone A, as there is no capacity added at the regional (zone A+B) level. Moreover, if the objective of zone A is to restore its security of supply to the optimal level, it will fail to do so if it applies cross-border participation. Therefore, zone A might be incentivized to overshoot its capacity target by not applying cross-border participation, implementing an additional capacity margin, or limiting the interconnectivity.

Authors

Emma Menegatti

FSR, RSCAS, EUI

emma.menegatti@eui.eu

Leonardo Meeus

FSR, RSCAS, EUI

leonardo.meeus@eui.eu