Capacity mechanism and explicit cross-border participation: a bad idea to fix a non-existing problem

Benoit Peluchon*

EDF R&D

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Abstract

The European Commission position about capacity mechanisms has evolved following the 2022-2023 energy crisis. The 2024 Market Design directive states that capacity mechnisms are no longer transitory measures but have a ”structural” role. This evolution renews the debate about their organisation and their possible europeanisation (ENTSOE 2025). The Clean Energy Package requires the participation of foreign capacities to a national mechanism, under the modality deemed ”explicit”: capacities in a country can be directly remunerated by a capacity mechanism in another country. The analysis of the different modalities of cross-border participation in a long-run competitive equilibrium model clearly shows that explicit participation is either useless or that it degrades the efficiency of the capacity mechanism. Moreover, this analysis questions the very existence of a negative externality that a capacity mechanism would cause to its energy only neighbours. Yet, this externality is the main justification for the explicit cross-border participation requirement.

Keywords: Electricity; Market design; Adequacy Capacity mechanism.

*EDF R&D SYSTEME Department, EDF Lab Paris-Saclay 1, boulevard Gaspard Monge 92120 Palaiseau France, e-mail: *benoit.peluchon@edf.fr*.

1 Introduction

The European Commission position about Capacity Requirement Mechanisms (CRMs) has evolved following the 2022-2023 energy crisis. The 2024 Market Design directive states that capacity mechnisms are no longer transitory measures but have a ”structural” role. Many countries are now considering them, joining France, Belgium, Ireland, Italy and Poland. Germany, previously opposed to capacity markets, and Sweden are considering implementing such schemes. This new dynamic gives new urgency to the debate about the best design of a CRM and its possible europeanisation (ENTSOE 2025). Usually, it is considered that a CRM can take many forms : a capacity market, a capacity payment, or strategic reserves. A capacity market sets a capacity target, then lets the price of capacity be determined by some competitive schemes (auctions, secondary market, etc.). A capacity payment sets directly the price of capacity in order to incentivize investors to install more capacity. A strategic reserve is the direct procurement of some additional capacity by the TSO, with the provision that whenever the reserve is activated, the spot price is set at the Value of Loast Load (VoLL), even when no load shedding is needed to balance supply and demand. In some way, a strategic reserve is not really a CRM, since it does not change the investment incentives but simply add capacity procured out of market. Two of the three european countries (Sweden, Germany) that implemented them are considering moving towards a capacity market. We will then focus in the remainder of the paper on capacity markets (CM), which are the dominant form of CRM being implemented in the European Union.

The Clean Energy Package requires that foreign capacities can participate to a national CM. This requirement is seen as the logical consequence of a non-discrimination principle and is a formal condition for the European Commission approbation of a national CRM scheme (given that it is seen as a State aid). This participation can take different forms: (1) implicit, i.e. foreign capacities contribution through interconnections are taken into account in the assessment of the level of capacity required but are not remunerated ; (2) explicit, i.e.

they are taken into account and remunerated up to a level, the Maximum Entry Capacity (MEC). MEC is the maximal contribution of foreign capacities to domestic security of supply, given interconnection capacities between the two countries. A methodology to estimate the MEC has been described by ACER (2020). Explicit participation is seen as mandatory by the European Commission. ACER notes in 2023 that it is not yet implemented in most countries. It has been set-up in some mechanisms : in Poland (border with Sweden), in Italy (with Montenegro) and in Belgium (first auction in 2024). France will implement explicit participation in its new centralized capacity market beginning in 2026.

Cross-border participation has been part of the french capacity mechanism from its beginning, since it was required by the European Commission in its approval decision in 2016. But it was implicit in its first years of operation, and then evolved toward a so-called "simplified" explicit mode : interconnectors were the participants until 2022 and the signature of bilateral deals with TSOs (with the exception of UK and Switzerland). The operation of this explicit participation has to be modified with the evolution of the french capacity market from a decentralized scheme to a centralized one : a capacity target is formally defined by the french TSO (RTE) and centralized auctions for capacities have to be set-up. RTE is thus thinking about new modalities in order to implement cross-border participation into the new capacity market design. Pre-auctions at each border seem to be the privileged model. A bidirectional TSO-TSO deal has been announced with Belgium and should allow explicit participation for the first deliveries.

The paper is organized as follows: the litterature is reviewed in the next section. The investment model and the capacity mechanism representation are presented in section 3. A second interconnected country is introduced in section 4, while the different modalities of cross-border participation in the CRM of one country are exposed in section 5. Long-run equilibrium in the explicit and implicit cases are compared. Section 6 presents a critique of the negative externality idea. Finally, section 7 concludes.

2 Litterature review

The interest of implementing a CM has been discussed for a long time in the litterature. The usual argument in favor of a CM is to remark that a price cap on the wholesale market (and/or out of market interventions by the TSO) leads to "missing money" for new or existing capacity, since the price is below the Value Of Lost Load (VOLL) i.e. the electricity consumption gross surplus. Joskow (2006, 2007, 2008) and Cramton & Stoft (2005, 2008) are classic papers making that case. If there is no price cap and no market imperfection, and a capacity target is set higher than the competitive equilibrium in an Energy Only (EO) setting, then a CM leads to a loss of expected net surplus for consumers, as remarked by Lambin & Léautier (2019). A better argument in favor of a CM is the impact of investors risk aversion, as reflected in the financial markets equity risk premium. The market revenues of a peak power plant are extremely volatile: they may be negative for many years before turning massively positive (when the market price reaches the Value Of Lost Load or the price cap due to load shedding). As a consequence, the cost of capital for peak capacity investment in an Energy Only market should be very high, as Peluchon (2019) argues in a CAPM setting, Ehrenmann & Smeers (2011a) with a CVaR risk criterion, or Petitet Finon Janssen (2017) with an exponential utility function. In that case, installed capacity will be too low to resepect a Security of Supply (SoS) standard, and a CM has many good properties: it allows to build more capacity but also lowers the cost of capital, since capacity remuneration is much less volatile than wholesale market revenues. It is then possible to lower total cost of generation compared to the EO results (see Peluchon 2019 for some evidence on french datas). This is not true for a strategic reserve, since the cost of capital for peak capacity investment is not lowered. This positive outcome of a CM (a better SoS and lower generation costs at the same time) is defended by RTE (France's TSO) in its impact assessment in 2018 of the capacity market, writing that a CM is a welfare improving regulation. The logic behind is very neatly summarized by Sisternes & Parsons (2016): "Shifting the structure of profit to one in which the same total revenue is paid for capacity across a broader number of hours provides a better, more reliable signal to investors, which lowers the cost of capacity to society." This impact of uncertainty is due to the absence of long term hedging instruments allowing risk transfers between consumers and producers, a "missing market" problem (Newbery 2016, de Maere Ehrenmann & Smeers 2016).

In the European Union, an important part of electricity is exchanged between Member States through interconnections. Implicit participation is a common sense idea: taking into account the possible mutualisation of capacities brought by exchanges in the determination of a capacity target is simply a requirement to prevent overprocurement. The litterature often present implicit participation as a "coordination" between countries, by opposition to "national" schemes where the target is set without implicit participation. But, in so far as a capacity market is a national mechanism, it may seem strange to require a country to remunerate non-domestic generation capacities, which cannot be constrained by what is by definition a national requirement, and whose contribution to national Security of Supply are potentially limited by interconnection capacities. One argument in favour of explicit participation is that setting up a CM in a country has defavorable consequences for its neighbours who keep an Energy Only model. For Lambin Léautier (2019) or Menegatti Meeus (2024a), who talk about a negative externality, installed capacity in the EO country will decrease in a long-run equilibrium. The reason can be summarized as thus: compared to a long-run equilibrium with two EO countries, when one country sets up a capacity market, it sees higher installed capacity, inducing lower wholesale electricity prices, which in return cause a decrease of installed capacity in the EO country. There is a partial displacement of capacity from one country to the other, and even a perfect one in Lambin Léautier (2019). Their result is underlied by two important assumptions : electricity consumption probability distribution is the same in each country (consumptions are thus perfectly correlated) and interconnection capacity is unlimited. The displacement of capacity from EO country to CM country is perfect in that case, and the price of capacity is zero. This extreme case allows to underline what is viewed as problematic with a CM: it is perceived as a form of predation from one country (”free rider” for Lambin & Léautier) toward its neighbour(s), potentially without any enhancement of global Security of Supply.

Other papers find that there is a capacity displacement, but some of their assumptions and / or methods may be criticized. More specifically, long-run investment incentives are not rigorously represented, and / or different market imperfections may coexist, blurring the analysis (capacity displacement may have other causes than a neighbour implementing a CM). As remarked by Bublitz et al (2019): ”One of the difficulties encountered in the study of cross-border effects is the large number of influence factors such as the regarded markets, generation technologies, different interconnector capacities or asymmetric market sizes. Furthermore, cross-border effects are strongly influenced by competition between market participants and the possibility of exerting market power. Thus, deriving common conclusions is extremely challenging.” For example, Meyer & Gore (2015) results lie in the assumption of imperfect competition. When the two countries have an Energy Only design, the exercise of market power allows generators to recoup some the missing money preventing them to install enough capacity ; when one of the two country implements reliability options, this lowers the incentives to mark up prices in this country, and increases competition through exports in the remaining EO country, finally leading to lower installed capacity. The negative impact is thus caused by the reduction of imperfect competition brought by the CRM. Höschle et al. (2018) also use an imperfect competition setting and find lower installed capacity in the EO country, when one neighbour estalishes a CM and another a strategic reserve.

In the case of Bucksteeg et al. (2019), who use an optimization model, the fact that existing capacities are included in the simulations implies that long-run investment incentives are not properly analyzed. Furthermore, the asymetric case (some countries establish a CM, some remain EO), does not seem to include the contribution of its neighbour’s capacities in the computation of the national capacity targets: the impact on EO countries is thus overestimated. Bhagwat et al. (2017) is an agent-based modelling work with bounded rationality (future demand expectations are based on past demand growth). They find a capacity displacement, but no degradation of SoS of the EO country. As they remark, EO consumers are free riding the CM country. Fraunholz et al. (2023) add risk aversion, as modelled through a CVaR criterion (which excludes best scenarios from expected margins), to imperfect competition (investment decided through some form of profit maximization) through capacity retention. The authors conclude that risk aversion amplify the negative impact on EO countries. But since there is imperfect competition, as in Meyer & Gore (2015), it should be caused by a more competitive equilibrium. Energy not served in EO countries increases, but since there is no indication about the value given to VoLL, or what happens to the wholesale price whenever there must be curtailments, it is difficult to understand what explains this increase. Furthermore, as existing power plants are included in the simulation and that renewable generation development is exogenous, there are imperfect long-run investment incentives.

Cepeda & Finon (2011) claim there is a negative externality for the EO country using a system dynamics model. But their results show a decrease of LOLE for this country when its neighbour establishes a CM, albeit as an average on the 30 years simulated. Furthermore, the capacity target for the latter does not take into account the possibility of imports from its neighbour, thus overestimating the capacity level needed. Cepeda (2018) pleads in favour of explicit participation of cross border capacities in capacity markets. Its interest is that interconnection investments are included in the dynamic model from Finon & Cepeda (2018). To our knowledge, it is the only article doing this, allowing to disentangle the impact of a capacity market from unoptimal interconnection capacity. It also clearly distinguishes implicit and explicit participation. France and UK datas are used for 2015-2035 simulations. Unfortunately, the only asymetric case studied (one country EO, one country CM) does not include cross border participation (not even implicit). Thus the real conclusions of the article should be that explicit participation when the two countries have a capacity market is a better regulation than implicit participation. The differences between the implicit and the explicit case are small and could be caused by some other assumptions. Furthermore, the case analyzed is really different from the present regulation: in their simulations, France sees a gradual decline of nuclear capacity due to the old 50 % nuclear share target that has been discarded since then, a gradual increase of CCGTs and an increase of CO2 emissions. Mengerink (2021) studies the value cross-border capacity can have for a CM, and finds a small positive value in the case of France and UK. But the results presentation is very fragmentary, and does not allow to fully understand the methodology.

According to Menegatti & Meeus (2024), three other negative externalities affect the EO country: an increase of costs for consummers, a lower SoS (higher expected loss of load) and a distorsion of congestion rents. These externalities are mentionned in some of the articles mentionned above, which have different methodological approaches (short-run equilibrium or long-run equilibrium, imperfect competition or not, with or without risk aversion, etc.) and as thus are not necessarily consistent with each other. Furthermore, as mentionned by Finon (2014), the European Commission puts emphasis on capacity displacement as the main reason to establish an explicit participation requirement (European Commission 2013), as this would provide EO country capacity a supplementary remuneration: "a mechanism which excludes cross border participants could result in new generation capacity displacing imports. This would undermine the financial viability of generation in other member states and could have a negative impact on regional security of supply" (p.28). As a consequence, we will focus on this effect afterwards.

As the goal of a CM is to preserve investment incentives, the right setting to analyse the different modalities of cross-border participation is a long-run equilibrium, since it allows to assess the impact of the rules on installed capacities (as remark Lambin & Léautier 2019). Interconnection capacity is also endogenous, allowing us to disentangle the CM rules impact from unoptimal interconnection capacity. Menegatti Meeus (2024) show with a numerical simulation that the long-run equilibrium is identical with implicit and explicit participation. We extend their results in three ways: firstly, we use an analytical model of the long-run equilibrium, allowing us to reach conclusions valid with any dataset ; secondly, we get results even if EO country capacities receive a positive remuneration from the CM country. In that case, marginal investment incentives are not modified in EO country, since only a part of its capacity get this additional remuneration. A rent is created, with negative consequences for CM country consummers, since their electricity bill increases without any additional benefit. Explict participation can thus degrade the economic efficiency of a CM. Finally, we conclude that there is no negative externality for an EO country whose neighbour establish a CM, but a positive one: total capacity increases when interconnection capacities are binding and optimized, and the neighbor's security of supply is not weakened as the European Commmission seems to think. There is no "Domino effect", when interconnection capacity is optimal.

3 Long-run investment model

We present here the long-run investment model, whose setting is close to Creti & Fabra (2004) or Lambin & Léautier (2019). Demand is stochastic and generation capacities are decided before its realization is known. In a second stage, demand is known and generation dispatch decisions are made given the capacities decided at the first stage. This model accomodate different technologies, including variable renewables, but not electricity storage. It allows to simply expose the principles that will be used afterwards when analysing the two country model.

3.1 Optimal generation mix : total cost minimization

There are N states of nature t, corresponding at the same time to timesteps and realization of random variables for a given timestep. There are I different technologies. We note D_t the electricity demand for state of nature t, τ_t the probability of state of nature t multiplied by the timestep length. We nomalize such that $\sum_t \tau_t = 1$ (instead of 8760). Generation by technology i in state of nature t is q_{it}, its capacity is x_i, its variable cost v_i (including the cost of CO2), its fixed cost f_i (including O&M fixed cost and investment annuity).

The Value Of Lost Load (VOLL) is noted V. It is the gross surplus of electricity consumption, that is the level of price or cost for which consummers are indifferent between consumming or not consumming electricity (Joskow & Tirole 2007). With this assumption, there is thus an equivalence between minimizing total costs and maximizing consummers surplus, since consummers' gross surplus is equal to total consumption times VOLL. Load shedding is represented as a fictional technology with zero fixed costs and a variable cost equal to VOLL allowing to fullfill demand.

The problem is to determine optimal capacities and generation dispatch in each state of nature in order to minimize the cost of fullfilling demand.

The objective function is:

$$min_{x,q} \sum_i (f_i x_i) + \sum_t \sum_i \tau_t v_i q_{it}$$

With decision variables: $x = (x_1, ..x_i.., x_I)$, $q = (q_{11}, ..q_{it}.., q_{IT})$

Remark that the objective function can be written equivalently:

$$min_{x,q} \sum_i f_i x_i + \mathbb{E}\left[v_i q_i\right]$$

q_i is a random variable whose realization q_{it} has probability τ_t.

We want to minimize the objective function under the following constraints (with dual variables between brackets):

$$D_t \leq \sum_i q_{it} \ (\lambda_t)$$

$$q_{it} \leq x_i \ (\mu_{it})$$

It is a perfectly standard linear programm. First order conditions are summed up by the following complementarity equations:

$$0 \leq f_i - \sum_t \mu_{it} \perp x_i \geq 0 \; \forall i$$

$$0 \leq \tau_t v_i + \mu_{it} - \lambda_t \perp q_{it} \geq 0 \; \forall i \; \forall t$$

$$0 \leq x_i - q_{it} \perp \mu_{it} \geq 0 \; \forall i$$

$$0 \leq D_t - \sum_i q_{it} \perp \lambda_t \geq 0 \; \forall t$$

A complementarity equation can be read as an equilibrium equation: either the left expression is strictly positive and the right expression zero, or the left expression is zero and the right expression strictly positive (see Ehrenmann & Smeers 2011b for a presentation of complementarity equations in an equilibrium model).

For every strictly positive installed capacity (for example $x_i > 0$), we have equality between the fixed costs and the sum of inframarginal rents ($f_i = \sum_t \mu_{it}$). Alternatively, if capacity x_i is zero, then $f_i > \sum_t \mu_{it}$. Likewise, generation of power plant i in state t (q_{it}) is strictly positive if the system marginal cost in state t (λ_t) is equal to the sum of of its variable cost (v_i) and its inframarginal rent (μ_{it}). The inframarginal rent is strictly positive if and only if capacity of power plant i is equal to its generation in state t (q_{it}). It is equal to the difference between the system marginal cost at time t (λ_t) and the variable cost of power plant i. Finally the system marginal cost is equal to the variable cost of the marginal power plant, if it is not generating at full capacity ($\mu_{it} = 0$).

3.2 Load factors at optimum

Load factors at optimum are defined by the equalization between fixed costs increase and variable costs decrease. We have:

$$f_i = \sum_t \mu_{it}$$

$$f_i = \sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\lambda_t - \tau_t v_i)$$

$$f_i = \sum_{t \in \{\lambda_t \geq \tau_t v_{i+1}\}} (\lambda_t - \tau_t v_{i+1}) + \sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\tau_t v_{i+1} - \tau_t v_i)$$

$$f_{i+1} = \sum_{t \in \{\lambda_t \geq \tau_t v_{i+1}\}} (\lambda_t - \tau_t v_{i+1})$$

Thus :

$$f_i = f_{i+1} + \sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\tau_t v_{i+1} - \tau_t v_i)$$

$$f_i - f_{i+1} = \sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\tau_t v_{i+1} - \tau_t v_i)$$

Variable costs are exogenous, thus:

$$f_i - f_{i+1} = (v_{i+1} - v_i) \sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\tau_t)$$

Where $\sum_{t \in \{\lambda_t \geq \tau_t v_i\}} (\tau_t)$ is the expectation of the load factor, normalized at 1. This quantity is analogous to a probability.

We retrieve the classic equations in a screening curve model:

$$(v_{i+1} - v_i)\, d_i = (f_i - f_{i+1})$$

Regarding total capacity adjustment, remark that the equality between the peak power plant fixed costs and its inframarginal rents implies that the marginal cost for a given state t may not be equal to the peaker variable cost or the VOLL. Let's take an example: if the peak power plant fixed costs are 65 000 €/MW, its variable cost 100 €/MWh, VOLL 20 000 €/MWh then the Loss of Load Expectation should be 3,27 hours. If the timesteps / states length is one hour, then the system marginal cost will equal VOLL for 3 states and 5 300 €/MWh for one other state. For this state, generation will equal total capacity and demand, so there is a positive inframarginal rent, but the marginal cost is lower than VOLL (no loss of load). Its value is given by the equality between fixed costs and the sum of inframarginal rents.

In order to show it rigorously, remind that load shedding is modeled as a fictional technology with variable cost V and no limited capacity. We have the following complementarity equation:

$$0 \leq \tau_t V - \lambda_t \perp def_t \geq 0 \; \forall i \; \forall t$$

For the state t when the peak power plant generates at full capacity and there is no loss of load, we have:

$$q_{js} = x_j \Rightarrow \mu_{js} > 0$$

There is a an inframarginal rent, but we also have:

$$def_s = 0 \Rightarrow \lambda_s < V$$

The marginal cost for this state is lower than V and higher than v.

Since the peak power plant capacity is strictly positive, we have:

$$f = \sum_t \mu_{jt} = \sum_{t \in \{t / D_t \geq x_j\}} \mu_{jt} = 3 \times (V - v) + \lambda_s$$

$$\lambda_s = f - 3 \times (V - v)$$

With the parameter values of our example we find a marginal cost equal to 5 300 €/MWh.

Afterwards we assume that the size of a timestep / state is much lower than an hour, since it represents different realizations of demand for a given hour of the year. The size is the probability of the state.

3.3 Costs and prices

One of the main characteristic of the optimal mix is that the short-run marginal cost reflects the long-run marginal cost. Pricing generation at the short-run marginal cost allows fixed costs recovery. We can indeed write at the optimum :

$$\sum_t \lambda_t D_t = \sum_t \left(\lambda_t \sum_i q_{it} \right) = \sum_i \sum_t \lambda_t q_{it}$$

$$\sum_t \lambda_t D_t = \sum_i \sum_t \left(\tau_t v_i + \mu_{it} \right) q_{it}$$

$$\sum_t \lambda_t D_t = \sum_i \sum_t \left(\tau_t v_i \right) q_{it} + \sum_i \sum_t \mu_{it} q_{it}$$

Since for each state t power plant i inframarginal rent is zero when generation is lower than its installed capacity, we can write:

$$\sum_t \lambda_t D_t = \sum_i \sum_t \tau_t v_i q_{it} + \sum_i \sum_t \mu_{it} x_i$$

$$\sum_t \lambda_t D_t = \sum_i \sum_t \tau_t v_i q_{it} + \sum_i x_i \sum_t \mu_{it}$$

$$\sum_t \lambda_t D_t = \sum_i \sum_t \tau_t v_i q_{it} + \sum_i x_i f_i$$

$$\sum_t \lambda_t D_t = \sum_i \left[v_i \sum_t \tau_t q_{it} + x_i f_i \right]$$

$$\sum_t \lambda_t D_t = \sum_i \left[v_i \sum_t \tau_t q_{it} + x_i f_i \right]$$

We get that the marginal cost weighted sum of total generation is equal to total costs. We have equivalence between cost minimization and perfect competition: the system marginal cost is the wholesale electricity price. From then on, we will use marginal cost or wholesale price indifferently.

3.4 Capacity Market

The introduction of a CM is underlied by the assessement that an Energy Only design cannot yield a satisfying level of Security of Supply (SoS). Different factors can be at play: a price cap lower than VOLL, a too high financial risk for peak capacity investment (see Peluchon 2019 or Ehrenmann Smeers 2011a), etc. The level of SoS in France is defined by law as a Loss of Load Expectation (LOLE) of three hours maximum. The SoS criterion defines a level of total capacity needed $\hat{x}$ given by the following equation:

$$\mathbb{P}\left(D_t \geq \hat{x}\right) = \frac{3}{8760}$$

With a CM exists a requirement that total capacity reaches this level. The following constraint is added to the previous optimization problem and allows to modelize a perfectly competitive capacity market:

$$\sum_i x_i \geq \hat{x} \ \ (\eta)$$

The dual variable η is the marginal cost of capacity, and, hence, the price of capacity in a perfectly competitive capacity market. We thus get the following complementarity equation among the first order conditions of the investment problem with the added capacity constraint:

$$0 \leq \sum_i x_i - \hat{x} \perp \eta \geq 0$$

We can remark that the price of capacity η is zero if installed total capacity is higher than the capacity target. In other words the capacity requirement does not create additional costs if the Energy Only investment level is already sufficient to meet the SoS criterion.

The previous first order conditions on capacity are modified thus:

$$0 \leq f_i - \sum_t \mu_{it} - \eta \perp x_i \geq 0 \; \forall i$$

This equation shows that if η is strictly positive, then the sum of inframarginal rents for power plant i with the CM is lower than it would be in the Energy Only case. Furthermore, we can note that all capacities are remunerated through price η since all contribute to the respect of the capacity target.

4 Two interconnected Energy Only countries

We simplifiy the previous problem by keeping only one technology. There are two countries A and B wich can be interconnected through a line of capacity T. The unitary cost of interconnection is noted c_T. We also note q_{At} the generation in country A used for domestic consumption and q^x_{At} the generation in country A used for consumption in country B (export).

The objective function becomes :

$$min_{\left\{x_i, q_{it}, q^x_{it}, Def_i, T\right\}} \, fx_A + fx_B + c_T T + \sum_t \left[\tau_t v \left(q_{At} + q^x_{At} + q_{Bt} + q^x_{Bt}\right) + \tau_t V \left(def_{At} + def_{Bt}\right)\right]$$

under the constraints (with the dual variables between brackets):

$$D_{At} \leq q_{At} + q^x_{At} + def_{At} \;\; (\lambda_{At}) \qquad \forall t$$

$$q_{At} + q_{At}^x \leq x_A \;\; (\mu_{At}) \qquad \forall t$$

$$q_{At}^x \leq T \;\; (\alpha_{At}) \qquad \forall t$$

$$D_{Bt} \leq q_{Bt} + q_{Bt}^x + def_{Bt} \;\; (\lambda_{Bt}) \qquad \forall t$$

$$q_{Bt} + q_{Bt}^x \leq x_B \;\; (\mu_{Bt}) \qquad \forall t$$

$$q_{Bt}^x \leq T \;\; (\alpha_{Bt}) \qquad \forall t$$

The Lagrangian is:

$$L = fx_A + fx_B + c_T T + \sum_t \left[\tau_t v \left(q_{At} + q_{At}^x + q_{Bt} + q_{Bt}^x\right) + \tau_t V \left(def_{At} + def_{Bt}\right)\right]$$

$$-\sum_i \sum_t \lambda_{it} \left(q_{it} + q_{jt}^x + def_{it} - D_{it}\right) - \sum_i \sum_t \mu_{it} \left(x_i - q_{it} - q_{it}^x\right) - \sum_i \sum_t \alpha_{it} \left(T - q_{it}^x\right)$$

Index i now refers to the country, j to the other country. We get the following complementarity equations:

$$0 \leq f_i - \sum_t \mu_{it} \perp x_i \geq 0 \qquad \forall i \in [A, B]$$

$$0 \leq \tau_t v + \mu_{it} - \lambda_{it} \perp q_{it} \geq 0 \qquad \forall i \in [A, B], \forall t$$

$$0 \leq \tau_t V - \lambda_{it} \perp def_{it} \geq 0 \qquad \forall i \in [A, B], \forall t$$

$$0 \leq \tau_t v + \mu_{it} + \alpha_{it} - \lambda_{jt} \perp q_{it}^x \geq 0 \qquad \forall i \in [A, B], \forall j \in [A, B], j \neq i, \forall t$$

$$0 \leq x_i - q_{it} - q_{it}^x \perp \mu_{it} \geq 0 \qquad \forall i \in [A, B], \forall t$$

$$0 \leq T - q_{it}^x \perp \alpha_{it} \geq 0 \qquad \forall i \in [A, B], \forall t$$

$$0 \leq q_{At} + q_{Bt}^x + def_A - D_{At} \perp \lambda_{At} \geq 0 \qquad \forall t$$

$$0 \leq q_{Bt} + q_{At}^x + def_B - D_{Bt} \perp \lambda_{Bt} \geq 0 \qquad \forall t$$

$$0 \leq c_T - \sum_i \sum_t \alpha_{it} \perp T \geq 0$$

If we look at the global optimum (combining the two countries), we get the usual equations but with the possibility that exchanges can be constrained by the interconnection capacity. Ths capacity is defined by the level which allows equality between the cost of development of one unit of interconnection capacity (c_T) and the sum of congestion rents ($\sum_i \sum_t \alpha_{it}$).

The dual variable α_{At} is strictly positive when exports fom country A to country B are equal to the interconnection capacity. When there is no congestion, we have $\alpha_{At} = \alpha_{Bt} = 0$ and then:

$$\tau_t v + \mu_{At} = \lambda_{At}$$

$$\tau_t v + \mu_{At} = \lambda_{Bt}$$

Or:

$$\lambda_{At} = \lambda_{Bt}$$

The marginal cost in the two countries are then equal. If we have a congestion, for example $\alpha_{At} > 0$ then:

$$\tau_t v + \mu_{At} = \lambda_{At}$$

$$\tau_t v + \mu_{At} + \alpha_{At} = \lambda_{Bt}$$

Or:

$$\lambda_{At} = \lambda_{Bt} - \alpha_{At}$$

The marginal cost of A is then lower than the marginal cost of B.

5 Two interconnected countries, one with a CM

We now study the optimum when country A establishes a CM while country B remains in an Energy Only design. We assume that the Energy Only investment level in A is lower than its SoS implied capacity target (i.e. the capacity target is binding in A). We now talk about country CM and country EO instead of A and B to allow a simpler exposition of the results. We first study implicit participation, i.e. without CM remuneration of EO country capacities, then we turn to explicit participation. Note that this one assume many actions for the TSO of CM country: EO capacities which want to participate must be certified, some control processes must be defined to check effective availability of those capacities, and penalties must be defined in case of non-availability. Those actions require a deal with CM country TSO. There are two modalities of explicit participation: the first one with pre-auction at the border, the second one with remuneration of a part of EO capacities at the capacity price of CM country. These two cases are distinct in that in the first it is possible to get two different capacity prices, whereas in the second there is only one capacity price for domestic and non-domestic capacities. The second case is envisionned by Menegatti and Meeus (2024b, Box 1 option 4) and made possible if the interconnector does not auction transit rights.

5.1 Implicit participation

Country CM establishes a capacity market in order to get a defined level of SoS, translated into a capacity target. Implicit participation of non domestic capacities simply means that the capacity target takes into account their contribution through imports when demand is high. According to the joint probability distribution of the two countries consumptions, this can (or cannot) lower country CM capacity target compared the case without power exchanges.

The objective function is identical to the one used in the previous part, a constraint is added to the problem:

$$\hat{x}_{CM} \leq x_{CM} \ (\eta)$$

We get the following complementarity equations:

$$0 \leq f - \sum_t \mu_{CMt} - \eta \perp x_{CM} \geq 0$$

$$0 \leq f - \sum_t \mu_{EOt} \perp x_{EO} \geq 0$$

$$0 \leq x_{CM} - \hat{x}_{CM} \perp \eta \geq 0$$

$$0 \leq \tau_t v + \mu_{it} - \lambda_{it} \perp q_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq \tau_t V - \lambda_{it} \perp def_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq \tau_t v + \mu_{it} + \alpha_{it} - \lambda_{jt} \perp q^x_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall j \in [CM, EO], j \neq i, \forall t$$

$$0 \leq x_i - q_{it} - q^x_{it} \perp \mu_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq T - q^x_{it} \perp \alpha_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq q_{CMt} + q^x_{EOt} + def_{CMt} - D_{CMt} \perp \lambda_{CMt} \geq 0 \qquad \forall t$$

$$0 \leq q_{EOt} + q^x_{EOt} + def_{EOt} - D_{EOt} \perp \lambda_{EOt} \geq 0 \qquad \forall t$$

$$0 \leq c_T - \sum_i \sum_t \alpha_{it} \perp T \geq 0$$

5.2 Border auctions

The capacity market in CM country is implemented through a national capacity target and Maximum Entry Capacity (MEC), i.e. the maximum level of non-domestic capacity that can participate given interconnection constraints. The MEC can be equal to capacity interconnection or lower taking into account the correlation between electricity demands in the two countries. If EO country capacities are greater than the MEC, then the price of capacity for non-domestic assets will be zero.

Indeed, the constraint is:

$$x_{EO} \geq T$$

Or:

$$x_{EO} \geq MEC$$

This will be always true as soon as demand in EO country leads to a greater installed capacity level. We will make this assumption, as in the case of France with one of its neighbour. We note $\hat{x}_{CM}$ CM country national capacity target.

We have the following Lagrangian:

$$L = f\left(x_{CM} + x_{EO}\right) + c_T T + \sum_t \left[\tau_t v\left(q_{CMt} + q^x_{CMt} + q_{EOt} + q^x_{EOt}\right) + \tau_t V\left(def_{CMt} + def_{EOt}\right)\right]$$

$$- \sum_i \sum_t \lambda_{it}\left(q_{it} + q^x_{jt} + def_{it} - D_{it}\right) - \sum_i \sum_t \mu_{it}\left(x_i - q_{it} - q^x_{it}\right)$$

$$- \sum_t \alpha_{it}\left(T - q^x_{it}\right) - \eta\left[x_{CM} - \hat{x}_{CM}\right]$$

First-order conditions are:

$$0 \leq f - \sum_t \mu_{CMt} - \eta \perp x_{CM} \geq 0$$

$$0 \leq f - \sum_t \mu_{EOt} \perp x_{EO} \geq 0$$

$$0 \leq \tau_t v + \mu_{it} - \lambda_{it} \perp q_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq \tau_t v + \mu_{it} + \alpha_{it} - \lambda_{jt} \perp q_{it}^x \geq 0 \qquad \forall i \in [CM, EO], \forall j \in [CM, EO], j \neq i, \forall t$$

$$0 \leq \tau_t V - \lambda_{it} \perp Def_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq x_i - q_{it} \perp \mu_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq T - q_{it}^x \perp \alpha_{it} \geq 0 \qquad \forall i \in [CM, EO], \forall t$$

$$0 \leq x_{CM} - \hat{x}_{CM} \perp \eta \geq 0$$

$$0 \leq q_{CMt} + q_{EOt}^x + def_{CM} - D_{CMt} \perp \lambda_{CMt} \geq 0 \qquad \forall t$$

$$0 \leq q_{EOt} + q_{CMt}^x + def_{EO} - D_{EOt} \perp \lambda_{EOt} \geq 0 \qquad \forall t$$

$$0 \leq c_T - \sum_i \sum_t \alpha_{it} \perp T \geq 0$$

We get the same first-order conditions than with the implicit participation case. Hence the competitive equilibriums are identical.

5.3 Positive remuneration of non domestic capacities

We can envision that non-domestic capacities get the same capacity price than domestic ones. But only a part of them will be able to be remunerated, given interconnection contraints. Hence we assume once more that installed capacity in EO country is greater than the MEC.

We note x_{EO_1} the capacities able to get this additional remuneration, and x_{EO_2} those who are not. As far as those capacities are not different, we do not indicate how this selection operates. For the demonstration, in a first time we assume that the capacity price p that capacities x_{EO_1} receive is exogenous (and such potentially different from capacity price η). The maximum level of EO country capacity that can receive p is MEC and ξ is the dual variable associated to this constraint.

We have the following Lagrangian:

$$L = f\left(x_{CM} + x_{EO_1} + x_{EO_2}\right) - p x_{EO_1} + \sum_i \sum_t \left[\tau_t v\left(q_{it} + q_{it}^x\right) + \tau_t V\left(def_{it}\right)\right]$$

$$-\sum_i \sum_t \lambda_{it}\left(q_{it} + q_{jt}^x + def_{it} - D_{it}\right) - \sum_i \sum_t \mu_{it}\left(x_i - q_{it} - q_{it}^x\right) - \sum_t \alpha_{it}\left(T - q_{it}^x\right)$$

$$-\eta\left[\hat{x}_{CM} - x_{CM}\right] - \xi\left[MEC - x_{EO_1}\right]$$

First-order conditions are modified as:

$$0 \leq f - p - \sum_t \mu_{EO_1 t} + \xi \perp x_{EO_1} \geq 0$$

$$0 \leq f - \sum_t \mu_{EO_2 t} \perp x_{EO_2} \geq 0$$

$$0 \leq MEC - x_{EO_1} \perp \xi \geq 0$$

For capacities EO_1 we have the equality:

$$f - p - \sum_t \mu_{EO_1 t} + \xi = 0$$

As $\xi > 0$, we have:

$$p + \sum_t \mu_{EO_1 t} > f$$

Capacities EO_1 get a remuneration greater than their total costs. Moreover, we also have:

$$\sum \mu_{EO_1 t} = f = \sum \mu_{EO_2 t}$$

Given that capacities EO_1 and EO_2 have identical variable costs.

It is obvious that the additional remuneration p only creates a rent without having an impact on investment incentives in EO country. This is true whatever the value of p, which can then be set equal to η without loss of generality.

There is thus no difference with the implicit mode competitive equilibrium. However, more capacities are remunerated at the same capacity price. As this cost is borne by CM country consumers, they pay more without getting any additional benefit in terms of SoS. With this observation, we can conclude that explicit participation degrades the capacity market economic efficiency.

6 A negative externality ?

Let's examine now the idea that establishing a CM in one country leads to negative consequences for its Energy Only neighbours (the negative externality already mentionned in the introduction). It is obvious that CM country capacity has increased compared to the case where the two countries are Energy Only. EO country capacity has probably decreased, but by the same or a lower amount ?

6.1 No interconnection constraint

In the case with no interconnection constraint, it is obvious that any increase in CM country capacity is exactly compensated by a decrease of EO country capacity. The probability distribution of prices is the same in the two countries (no congestion), thus the decrease of wholesale prices induced by more capacity in CM country will provoke a decrease of EO country capacity since the economic equation of capacity investment is unchanged. We get the same total capacity on the two countries, but with a displacement of capacity from EO to CM. It is the conclusion of the main case in Lambin & Léautier (2019) when there is no congestion. This is what Menegatti Meeus (2014a or 2014b) consider as a negative externality: the capacity requirement only impact is a capacity displacement. Remark that in that case, the capacity price is zero (Lambin Léautier 2019).

We can show this formally with the complementarity equations from the implicit case by excluding the last (interconnection) and the α_{it}. We have the following equation for EO country capacity:

$$f = \sum_t \mu_{EOt}$$

For CM country;

$$f = \sum_t \mu_{CMt} + \eta$$

Since the the probability distribution of wholesale prices is the same in the two countries:

$$\mu_{CMt} = \mu_{EOt} \quad \forall t$$

Therefore:

$$f = \sum_t \mu_{CMt} + \eta$$

$$\Leftrightarrow f = f + \eta$$

$$\Leftrightarrow \eta = 0$$

Capacity target is reached since η equals zero :

$$0 \leq x_{CM} - \hat{x}_{CM} \perp \eta \geq 0 \Rightarrow x_{CM} > \hat{x}_{CM}$$

Total capacity level can be retrieved by remarking that:

$$f = \sum_t \mu_{it} = \sum_{t \in \{t / D_{EOt} + D_{CMt} > x_{CM} + x_{EO}\}} \tau_t (V - v)$$

$$\Leftrightarrow \sum_{t \in \{t / D_{EOt} + D_{CMt} > x_{CM} + x_{EO}\}} \tau_t = \frac{f}{V - v}$$

This equation defines the Loss Of Load Expectation for the two countries taken together, and thus implicitely the level of total capacity. In the case when the two countries are EO, we have the same equation, and therefore the same total capacity level. But there is a catch:

this means that the SoS criterion is not respected in CM country with the implementation of the capacity market, since the level of load shedding allows to cover the fixed cost (when the price is equal to VOLL), and we made the assumption that an EO design in the two countries lead to a LOLE level higher than the SoS target. It also implies that when there are no interconnection constraint, it is not possible to define a national capacity target $\hat{x}$ for a capacity market.

6.2 Interconnection constraint and identical demands

If, on the other hand, there are congestions in some states of nature, which is the case if we introduce the constraint (and the cost) of the interconnection capacity, then the distribution of wholesale prices is not the same in the two countries, and EO capacity decreases less than the CM capacity increase.

To demonstrate that result, we examine first the case where the demands are identical in the two countries. If the two countries are EO, capacities are then the same in each country, thus there is no possibility to exchange electricity and no interconnection is built. This is no longer true if a country implements a capacity market. There is more capacity in CM country, hence the only possible exchanges are exports from CM to EO whenever demand is higher than EO country capacity (x_{EO}). Since exchanges are constrained by interconnection capacity (it has a cost), wholesale prices in EO are higher than in CM (α_{CMt} are strictly positive, while α_{EOt} equal zero) and the decrease of EO country capacity is lower than the capacity increase in CM country. Implementing a capacity market in one of the two countries yields an increase of the total capacity of the two countries.

More formally, we can regroup states of nature in three subsets: (1) those for which demand in one country is lower than x_{EO}, in which case the price is v and there are no exchanges

$$E_1 = \{t/D_{it} < x_{EO}\}$$

(2) those for which the demand in a country is higher than $x_{CM} = \hat{x}_{CM}$, in which case the price is V in the two countries and there are no exchanges

$$E_2 = \{t / D_{it} > x_{CM}\}$$

(3) those for wich demand in one country is set between x_{EO} and x_{CM}. There are exports from CM to EO, and two situations are possible: there is no congestion, and the prices are equalized by exchanges either at v or V ; there is some congestion, the price is V in EO country and v in CM country

$$E_3 = \{t / x_{CM} \geq D_{it} \geq x_{EO}\}$$

In other words, the margins from the wholesale market are the same for capacities in the two countries for states belonging to subset E_1 or subset E_2. For states belonging to E_3, margins are either equal or higher for EO country capacities.

Thus expected market revenues for EO capacities is higher than expected market revenues for CM capacities. Furthermore, the difference between the two values is equal to the cost of interconnection capacity.

We have indeed:

$$f = \sum_t \mu_{EOt} = \sum_{t \in \{t/\alpha_{CMt} > 0\}} \tau_t (V - v) + \sum_t \mu_{CMt}$$

For the states of nature when $\alpha_{CMt} > 0$:

$$\tau_t v + \mu_{CMt} = \lambda_{CMt}$$

$$\tau_t v + \mu_{CMt} + \alpha_{CMt} = \lambda_{EOt}$$

Then:

$$\alpha_{CMt} = \lambda_{EOt} - \lambda_{CMt}$$

Since:

$$c_T = \sum_i \sum_t \alpha_{it}$$

Finally, we get:

$$f = \sum_t \mu_{EOt} = c_T + \sum_t \mu_{CMt}$$

Moreover, at equilibrium we have:

$$f = \sum_t \mu_{EOt}$$

$$f = \sum_t \mu_{CMt} + \eta$$

$$\Rightarrow \sum_t \mu_{EOt} = \sum_t \mu_{CMt} + \eta = \sum_t \mu_{CMt} + c_T$$

$$\Rightarrow \eta = c_T > 0$$

The price of capacity is strictly positive and equal to c_T, the unitary cost of interconnection capacity. This allows to show that EO country capacity is higher than what it was in the previous case (identical demand, no interconnection constraint), and thus that the sum of capacities in the two countries is higher than its value when the two countries are EO. The fact that interconnection capacity has a cost implies the existence of some congestions, and they in return prevent that the capacity market implementation only displaces capacity between the two countries.

6.3 Interconnection constraint and different demands

If demands are not identical, we may have states of nature with imports or exports when the two countries are EO. Some interconnection capacity is built, financed by congestion rents. Equilibrium capacity levels in the two countries are not necessarily equal, but are such that the marginal costs (wholesale prices) allow to cover exactly the fixed costs of power plants. Compared to the previous case, we now have states of nature when CM country prices can be higher than EO country prices (with exports from EO to CM constrained by congestions, implying that some α_{EOt} are strictly positive).

Equilibrium when the two countries are EO is caracterised by the following equality:

$$f = \sum_t \mu_{At} = \sum_t (\lambda_{At} - \tau_t v) = \sum_t \mu_{Bt} = \sum_t (\lambda_{Bt} - \tau_t v)$$

$$f + \sum_t \tau_t v = \sum_t \lambda_{At} = \sum_t \lambda_{Bt}$$

We also have:

$$f + \sum_t \tau_t v = \sum_t \lambda_{At} = \sum_t \lambda_{Bt} - \sum_t \alpha_{At} + \sum_t \alpha_{Bt}$$

Thus :

$$\sum_t \lambda_{At} = \sum_t \lambda_{At} - \sum_t \alpha_{At} + \sum_t \alpha_{Bt}$$

$$\sum_t \alpha_{At} = \sum_t \alpha_{Bt}$$

The sum of congestion rents balance between the two countries, which is logical since costs are identical. We have furthermore:

$$c_T = \sum_t \alpha_{At} + \sum_t \alpha_{Bt}$$

$$\sum_t \alpha_{At} = \sum_t \alpha_{Bt} = \frac{c_T}{2}$$

We have two sets of states of nature: (1) without congestions, when the prices are equal in the two countries ; (2) states of nature with congestion, with a price of V in one of the country and a price of v in the other. The fact that the sum of congestion rents for a country are equal with the sum for the other is simply the consequence that generation fixed costs are the same.

If we implement a capacity target in one of the countries, its capacity will increase by definition (remember that we made the assumption that the EO level does not lead to respect of the SoS criterion). Since the distribution of prices in the EO country needs to allow generation fixed costs recovery, this implies that it is not respected in the EO country. We need to have different market revenues in the two countries, which means that the sum of congestion rents for each country will have to be asymetric.

More formally:

$$f = \sum_t \mu_{CMt} + \eta = \sum_t \mu_{EOt}$$

$$f = \sum_t (\lambda_{CMt} - \tau_t v) + \eta = \sum_t (\lambda_{EOt} - \tau_t v)$$

$$f + \sum_t \tau_t v = \sum_t \lambda_{CMt} + \eta = \sum_t \lambda_{EOt}$$

Revenues generated by wholesale prices in CM country are lower than the revenues generated by wholesale prices in EO country (since the SoS criterion is respected in CM country but not in EO country). It implies that the capacity price is strictly positive. We also have :

$$\sum_t \lambda_{CMt} + \eta = \sum_t \lambda_{EOt} = \sum_t \lambda_{CMt} - \sum_t \alpha_{EOt} + \sum_t \alpha_{CMt}$$

$$\eta = -\sum_t \alpha_{EOt} + \sum_t \alpha_{CMt}$$

As capacity price is strictly positive, congestions from CM to EO are greater than those from EO to CM.

Can we talk about a security of supply degradation for country EO ? No, since expected lost load is the same for this country whether the two countries are EO or the other implements a capacity market. It is true that in the second case it has less installed capacity, but CM country capacity has increased by a higher value, and as a consequence it can import more. In a way, it gets the same security of supply without bearing the same costs of investment. The costs for EO consumers are unchanged, since the equation ensuring equality between total costs of generation (including lost load) and the expectation of wholesale prices remains valid. Taking about a negative externality is thus unwarranted (we should even talk about a positive externality !), thus negating the main justification for the requirement to remunerate cross border capacities.

7 Conclusion

The analysis of the different modalities of cross-border participation clearly shows that explicit participation, today required by the European Commission, risk degrading the economic efficiency of a capacity market. Beyond the inherent complexity of its practical implementation, it either yields no additional remuneration for cross-border capacities (auctions at the borders) or an illegitimate rent which increases costs for the CM country consumers (one capacity price). This observation is obtained through an analytical long run investement model, an approach that has two advantages compared to the litterature on the subject: the long run equilibrium including interconnection investment allows to highlight the investment incentives in the different modalities studied ; the conclusions derived are valid whatever the values given to the parameters of the model. The main conclusion about explicit participation inefficiency is thus general. Furthermore, in that setting, it is not warranted to talk about a negative externality. Any EO country with a neighbour implementing a capacity market does not see its security of supply lowered, even if its installed capacity decreases. Since it is the main argument in favour of an explicit participation requirement, it seems legitimate to alleviate this requirement in order to allow european capacity market to operate efficiently.

References

ACER (2020). Technical specifications for cross-border participation in capacity mechanisms.

ACER (2023). Security of EU electricity Supply in 2022.

Bhagwat, P., Richstein, J., Chappin, E., Iychettira, K. & De Vries, L. (2017). Cross-border effects of capacity mechanisms in interconnected power systems. Utilities Policy, 46: 33–47.

Bublitz, A., Keles, D., Zimmermann, F., Fraunholz, C. & Fichtner, W. (2019). A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms. Energy Economics, 80: 1059–78.

Bucksteeg, M., Spiecker, S., & Weber, C. (2019). Impact of Coordinated Capacity Mechanisms on the European Power Market. The Energy Journal, Vol. 40(No. 2), p. 221-264.

Cepeda, M. (2018). Assessing cross-border integration of capacity mechanisms in coupled electricity markets. Energy Policy, 119: 28–40.

Cepeda, M., & Finon, D. (2011). Generation capacity adequacy in interdependent electricity markets. Energy Policy, 39, pp. 3128-3143.

Cramton, P., Stoft, S.(2005), A Capacity Market that Makes Sense. The Electricity Journal Volume 18, Issue 7, August–September 2005, Pages 43-54.

Cramton, P., Stoft, S. (2008), Forward reliability markets: Less risk, less market power, more efficiency. Utilities Policy, 16 (3), pp. 194-201.

de Maere, G., Ehrenmann, A., Smeers, Y. (2016), Investment with incomplete markets for risk: The need for long-term contracts, Energy Policy 105, 571583.

European Commission. (2013). Generation adequacy in the internal market: Guidance to optimize public interventions (Draft document), September 2013.

Ehrenmann, A., Smeers, Y. (2011a), Generation capacity expansion in a risky environment: a stochastic equilibrium analysis. Oper. Res. 59 (6), 1332-1346.

Ehrenmann, A., Smeers, Y. (2011b). Stochastic equilibrium models for generation capacity expansion. In: Bertocchi, Marida, Consigli, Giorgio, Dempster, Michael A.H. (Eds.), Stochastic Optimization Methods in Finance and Energy, volume 163 of International Series in Operations Research & Management Science. Springer, New York, 273–310.

ENTSOE. (2025). The role of Capacity Mechanisms to enable a secure and competitive energy transition. ENTSOE-E Policy Paper, April 2025.

Fabra, N. and A. Creti (2007), Supply Security and Short-Run Capacity Markets for Electricity, Energy Economics 29(2), 259-276.

Fabra, N., von der Fehr, N.-H.M., de Frutos, M.-Á., (2011). Market design and investment incentives. Economic Journal 121, 1340–1360.

Finon, D. (2014). Capacity mechanisms and cross-border participation: The EU wide approach in question. CEEM Working Paper 8, Paris-Dauphine University.

Fraunholz, C., Miskiw, K. K., Kraft, E., Fichtner, W., & Weber, C. (2023). On the Role of Risk Aversion and Market Design in Capacity Expansion Planning. The Energy Journal, pp. 111-138.

Höschle, H., Le Cadre, H., & Belmans, R. (2018). Inefficiencies caused by Non-Harmonized Capacity Mechanisms in an Interconnected Electricity Market. Sustainable Energy, Grids and Networks, Vol. 13, pp. p. 29-41.

Joskow P. L. (2006) “Markets for Power in the United States : An Interim Assesment.” The Energy Journal, 27(1): 1-36.

Joskow, P.L. (2007), Competitive electricity markets and investments in new generation capacity. In Helm, D. (ed.), The New Energy Paradigm, Oxford University Press, Oxford.

Joskow, P.L. (2008), Capacity payments in imperfect electricity markets: Need and design Utilities Policy, 16 (3), pp. 159-170.

Joskow, P. L., Tirole, J. (2007), Reliability and Competitive Electricity Markets, Rand Journal of Economics, 38 (1), 60-84.

Lambin, X. & Léautier, T.-O. (2019). Cross-Border Effects of Capacity Remuneration Schemes in Interconnected Markets: Who Is Free-Riding? The Energy Journal, 40(6): 79–110.

Menegatti, E. & Meeus, L. (2024a). Cross-Border participation: A false hope for fixing capacity market externalities? Working Paper, Florence School of Regulation, https://fsr.eui.eu/publications/?handle=1814/77489.

Menegatti, E. & Meeus, L. (2024b). An easy fix to streamline capacity markets. Policy Brief, Floren School of Regulation, https://fsr.eui.eu/publications/?handle=1814/77492.

Mengerink, R. (2021). Cross-Border Participation in Capacity Mechanisms. TU Delft.

Meyer, R., & Gore, O. (2015). Cross-border effects of capacity mechanisms: Do uncoordinated market design changes contradict the goals of the European market integration? Energy Economics 51.

Newbery, D. (2016), Missing Money and Missing Markets: Reliability, Capacity Auctions and Interconnectors, Energy Policy, 401-410.

Peluchon, B. (2019). Market-Design and the cost of capital for generation capacity investment. CEEM Working Paper 41, Paris-Dauphine University.

Petitet, M., Finon, D., & Janssen, T. (2017). Capacity adequacy in power markets facing energy transition: A comparison of scarcity pricing and capacity mechanism. Energy Policy, 103, pp. 30-46.

Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity. (2019). Official Journal of the European Union, L 158/54.

RTE (2018), Analyse d’impact du mécanisme de capacité. https://www.services-rte.com/files/live/sites/services-rte/files/pdf/MECAPA/MecaCapa_Analyse_impact_v5.pdf

Sisternes, F. J., Parsons, J. E. (2016), The Impact of Uncertainty on the Need and Design of Capacity Remuneration Mechanisms in Low-Carbon Power Systems, MIT CEEPR WP 2016-004