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APRIL 2026
CEEPR WP 2026-08

Working Paper Series.

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Cross-border Solidarity versus National Capacity Markets: Risk of Inadequate Capacity Procurement

Emma Menegatti, Leonardo Meeus

Abstract

In Europe, capacity markets are currently designed and operated at the national level, which can give rise to non-cooperative behavior. Member States may strategically influence national capacity procurement to maximize national welfare rather than cooperating towards the regionally optimal procurement. Using a stylized analytical model of two interconnected capacity markets, this paper evaluates the risk of such non-cooperative behavior. We differentiate between three options for the allocation of capacity markets' costs and benefits: local, reservation, and sharing. Under the current EU framework, the benefits of capacity markets are shared regionally, as curtailment sharing applies in the day-ahead market clearing algorithm in cases of simultaneous scarcity, while capacity procurement costs are borne nationally. Sharing benefits but not costs creates incentives for freeriding, potentially leading to regional under-procurement of capacity. Moreover, the absence of a direct link between procured capacity and curtailment allocation weakens incentives for implementing explicit cross-border participation in capacity markets. We identify three possible remedies: (i) maintaining the existing framework with ad-hoc cross-border compensations, (ii) modifying curtailment rules so that cross-border flows reflect national capacity procurement rather than solidarity, or (iii) sharing ex-ante capacity costs through a regional capacity market. As the first two options appear more difficult to implement and unsatisfactory in the long term, we argue that a regional or European capacity procurement approach is increasingly necessary, given rising interconnectivity and the expanding scope of capacity markets in Europe.

Keywords

Electricity, Adequacy , cross-border coordination , State Aid , Capacity market

1 Introduction

National capacity markets are gaining momentum in the EU, with five Member States already operating one (Belgium, France, Ireland, Italy, Poland), and at least five considering introducing one over the coming decade (Germany, Sweden, Spain, the Netherlands, and Denmark). Moreover, the electricity market design reform of 2024 has reconsidered the role of capacity mechanisms: they are no longer considered "last resort" or "temporary" measures, and their introduction will be streamlined. As national capacity markets become such widespread and structural elements of the EU electricity market design, it becomes crucial to ensure adequate cross-border coordination. In this paper, we assess whether the national-level operation of capacity markets is prone to non-cooperative behavior, resulting in inadequate capacity procurement. This depends on two coordination dimensions. First, who pays for the resource adequacy measures, i.e., how are the capacity costs allocated across the region? Second, who benefits from the resource adequacy measures, i.e., how is consumers' curtailment allocated across the region? For these two dimensions, we identify three allocation options: local, reservation, and sharing. Our contribution is to assess the compatibility of these different options. To do so, we verify whether the optimal capacity level, achieved in a "cooperative scenario", can be effectively be reached when capacity markets are operated at the national level, in a "non-cooperative scenario". We use an analytical model adapted from Lambin & Léautier (2021). While the latter focused on a capacity market with an energy-only market neighbor, we assess more in depth the effect of non-cooperative behavior with two symmetrical interconnected national capacity markets.

Focus - Inadequate capacity procurement Our paper focuses on the risk of over- or under-procurement of generation capacity. We identify two main drivers for such inadequate procurement. First is an imperfect assessment of the interconnected systems' complementarities. Interconnectivity reduces the need for domestic capacity when scarcity events are not perfectly correlated. Various numerical modelling analyses have assessed the reduction of capacity needs stemming from interconnectivity, compared to an autarky scenario. Hagspiel et al. (2018), Bucksteeg et al. (2019), and Astier and Ovaere (2022) found capacity gains of respectively 6%, 10% and 5%, considering various sets of European countries. In this paper, we will however assume two interconnected countries with perfectly correlated demands. As such, the interconnector does not reduce the regional capacity need. We instead focus on a second driver for inadequate procurement: non-cooperative behavior. In this case, inadequate procurement is a result of policy-makers' incentives to maximize consumers' surplus at the national level ("non-cooperative scenario"), rather than at the regional level ("cooperative scenario"). Such issue was notably assessed in Lambin & Léautier (2021), who evaluated the optimal response of an energy-only country to a capacity market neighbor, in an non-cooperative scenario with symmetrical demands.

In the EU, capacity markets are operated at national level. In theory, methodologies for defining the VOLL/CONE/RS (ACER, 2020a), conducting Resource Adequacy Assessments (ACER, 2020b), and enabling explicit cross-border participation (ACER, 2020c) allow to coordinate Member States' capacity demand definitions, and to avoid inadequate capacity procurement. Realistically, it remains possible for Member States to overshoot capacity procurement (or vice-versa, underprocure): through high Value of Lost Load (VOLL) assumptions, conservative de-rating factors, conservative hypotheses on demand price responsiveness, ambitious demand growth forecasts, or higher weighting of stress scenarios in national assessments. So, in this paper, we assume that policy-makers can influence national capacity demand definition in order to maximize their national welfare. Their incentive to do so depends on two regulatory dimensions, further described below.

Dimension 1 - Cost allocation Incentives to over- or under-procure capacity depend on who pays for the additional capacity, i.e. how capacity costs are allocated at regional level. In this paper, we evaluate three options. First, domestic consumers pay specifically for domestic capacity ("local"). Second, domestic consumers pay for the capacity procured, say through the domestic capacity market, irrespective of its location ("reservation"). Third, domestic consumers pay for half of the regional capacity costs ("sharing"). An illustration of these three rules is provided in Figure 1. We found limited literature focusing explicitly on how to allocate capacity costs at regional level. An exception is the litterature focusing on explicit cross-border participation, such as EMLab (2017), Finon (2018), Mengerink (2021), and Menegatti and Meeus (2024a).[1]

In the EU, explicit cross-border participation is mandatory since the Clean Energy Package (Electricity Regulation, 2019). Consumers in a country operating a capacity market should therefore pay for all domestic and foreign capacity procured. European legislation therefore resembles the "reservation" rule. However, the implementation of this rule remains lagging, and is likely to result in inefficient pricing, as we argue in Menegatti and Meeus (2024b). With the simpler alternative, implicit cross-border participation, consumers only pay for generation capacity within their local territory. The "local" rule therefore reflects the historical practice of consumers paying only for domestic generation capacity. An intermediate option, as implemented in the UK and France, consists in remunerating interconnectors. In our simple model, we consider that the interconnector is never binding (i.e., cross-border electricity exchanges are always smaller than the maximum cross-border transmission capacity), and therefore discard such option.

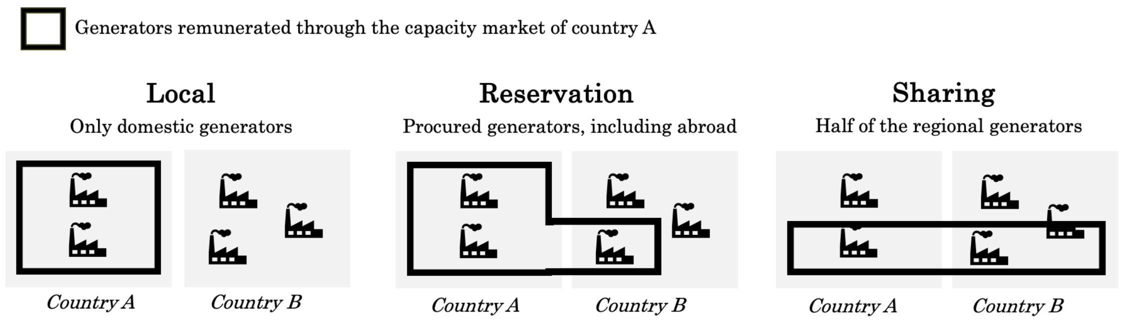

Figure 1: Capacity costs allocation rules

Dimension 2 - Curtailment allocation Incentives to over- or under-procure capacity depend also on who benefits from the additional capacity, i.e., how curtailment is allocated at regional level during simultaneous scarcity periods. In this paper, we consider three options. First, local generation can be allocated in priority to domestic consumers ("local"). Second, generation can be allocated in priority to consumers who reserved, say through explicit cross-border participation, the underlying capacity ("reservation"). Third, available generation can be shared equally across the consumers of the two countries ("sharing"). An illustration of these three rules is provided in Figure 2. Most modelling analyses looking at capacity markets from the regional level do not explicitly mention how curtailment is allocated across countries. An exception is Lambin & Léautier (2021), who describe and assess both curtailment sharing and local (refered to as "domestic priority").

[1] The question of how to allocate the costs of a given measure across countries when its benefits are partly shared at regional level has been discussed more extensively in the case of transmission infrastructure. For example, Glachant et al. (2017) argued for further regional coordination in this area.

In the EU, the prevailing curtailment allocation rule in case of simultaneous scarcity is "curtailment-sharing", as implemented by default in Euphemia [2]. Consumers' curtailment ratios are equalized in both countries, as much as allowed by the interconnection, following a solidarity principle. This appears incompatible with the domestic nature of adequacy policies. This particular issue was notably raised by Finon (2013), Henriot & Glachant (2014), Roques (2019), and Lambin & Léautier (2021). Some countries do not yet apply curtailment sharing, and therefore apply "local-matching" (Poland, Italy, and Slovenia) (MCSC, 2023). The "Local" rule is also considered realistic considering transmission system operators' ability and incentives to intervene to limit exports when anticipating a scarcity situation.

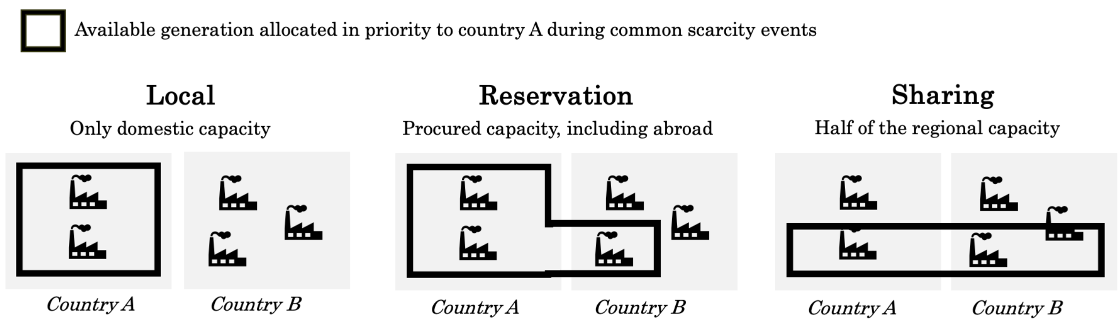

Figure 2: Curtailment allocation rules

In the following sections, we first introduce our analytical model (Section 2). Then, we provide our results (Section 3). We evaluate whether the optimal capacity level can be reached for the various configurations shown in Table 1. In particular, we show that the current regulatory framework could result in under-procurement of capacity, and we identify potential regulatory solutions. Next, we discuss qualitatively the challenges that would arise with implementing such solutions in the EU (Section 4). Finally, we discuss the limitations and possible extensions of our approach (Section 5), and conclude with recommendations (Section 6).

Table 1 - Coordination dimensions matrix

		Curtailment		
		Sharing	**Local**	**Reservation**
Costs	**Sharing**			
	Local	realistic practice	realistic practice	
	Reservation	current EU framework	realistic practice	

[2]More precisely, "curtailment sharing" applies when the demand cannot be met by the submitted supply bids, and day-ahead prices reach the price cap in the two countries.

2 Model description

In this section, we introduce our simple analytical model. We first describe the model set-up and main assumptions (2.1). Then, we describe the regional welfare components in a cooperative scenario (2.2), and the national welfare components in non-cooperative scenarios (2.3).

2.1 Model set-up

In this section, we describe our model set-up and main assumptions. An overview is provided in Figure 3 .

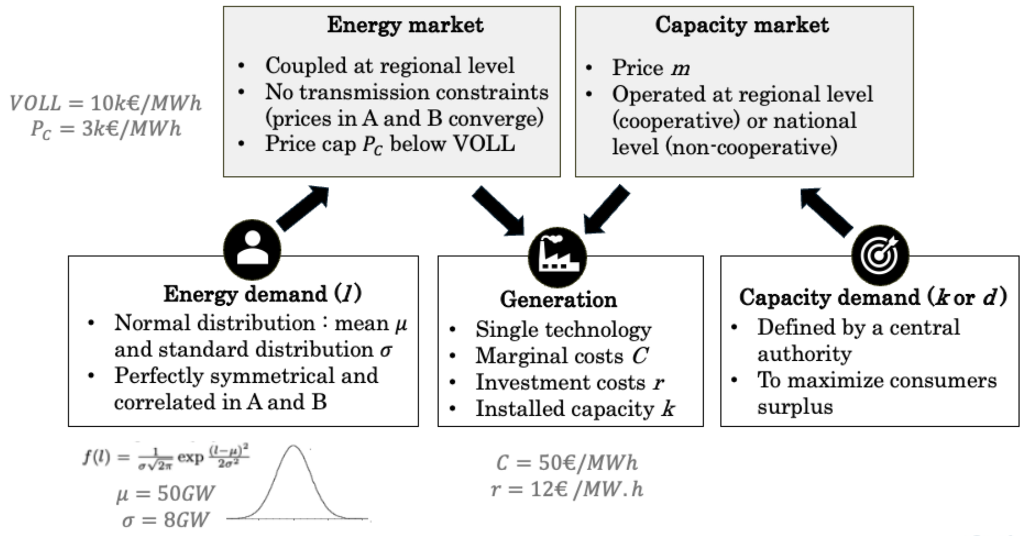

Figure 3: Model set-up and main assumptions

System We model an electricity system of two countries, noted A and B. They are symmetrical and interconnected. The interconnection is considered never binding, for simplification purposes.

Electricity generation One single technology is available in both zones with generation costs C (50 €/MWh) and investment costs r (12 €/MW.h). These costs are equal in A and B. The installed generation capacity at regional level (k_R) and at national level (k_A, k_B), are derived from the perfect competition assumptions, and depend on the market design configuration assumed.

Electricity demand The national energy demand l is assumed to be symmetrical, perfectly correlated (i.e., at any time period $l_A = l_B = l$), and inelastic. It follows a normal distribution f (such that $f(l) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{(l-\mu)^2}{2\sigma^2}$) of mean μ (50 GW) and standard distribution σ (8GW). We use the following notation: $F(k) = \int_0^k f(a)\,da$. The normal distribution function admits the following derivative (1) and probability density (2) functions:

$$f'(l) = -\frac{l-\mu}{\sigma^2} f(l) \tag{1}$$

$$\int_0^k l f(l)\, dl = \mu F(k) - \sigma^2 f(k) \tag{2}$$

Energy market Both countries operate a common and coupled energy market. Consumers value each unit of energy served at the national Value of Lost Load ($VOLL$=10 k€/MWh), in line with the demand inelasticity assumption. As transmission is never binding, the prices are always equal across the two countries. A price cap (P_c=3 k€/MWh) applies in the energy market for both zones, set below the national $VOLL$. By reducing the generators' scarcity revenues below optimal, the price cap represents a simple market failure, which justifies the introduction of capacity remuneration.

Reference optimal capacity The optimal national capacity level K^* can be derived from the economic equilibrium in a perfectly competitive energy-only market scenario. The generators' marginal profit should equal zero. As transmission is not binding, scarcity only materializes when the regional load exceeds the total available capacity ($2l \geq 2K^*$). The likelihood of scarcity is therefore $1 - F(K^*)$. The generator's profit in times of scarcity equals the market price minus its generation cost: $VOLL - C$. The cost of building additional capacity is the investment cost r. We therefore obtain the following condition:

$$(VOLL - C)(1 - F(K^*)) - r = 0 \tag{3}$$

Using the numerical values, we obtain the equilibrium capacity K^*=74.3 GW. We moreover obtain the loss of load expectation $LOLE^* = (1 - F(K^*)).365.24 = 10.6$ h/year.

Reduction of capacity considering the energy market price cap As per the previous paragraph, we can derive the equilibrium capacity considering the price cap, noted K^{eq}_{cap}. When scarcity materializes, prices are limited to the price cap P_C, instead of reaching the $VOLL$. We therefore obtain the following equilibrium condition:

$$(P_C - C)(1 - F(K^{eq}_{cap})) - r = 0 \tag{4}$$

Using the numerical values, we obtain the equilibrium capacity K^{eq}_{cap}=71.2 GW. The associated loss of load expectation $LOLE^{eq}_{cap} = 35.6$ h/year.

Capacity Market To restore adequacy, both countries operate individually a national capacity market. They are modeled through capacity payments m_A, m_B. To have non zero capacity values in both countries, the price must be equal in both countries : $m_A = m_B = m$. Moreover, in a perfectly competitive scenario, the total net revenues of the marginal generator, corresponding to scarcity revenues ($(P_c - C)(1 - F(\frac{K_A + K_B}{2}))$) minus investment costs (r) plus the capacity revenues (m) must be equal to zero: $(P_c - C)(1 - F(\frac{k_A + k_B}{2})) - r + m = 0$. Replacing r using (3), we obtain the following expression of the capacity price :

$$m(k_A, k_B) = (VOLL - C)(1 - F(K^*)) - (P_c - C)(1 - F(\frac{k_A + k_B}{2})) \tag{5}$$

Using the numerical values, we can compute the capacity payments m^* necessary to restore the optimal regional capacity ($k_A + k_B = 2K^*$). We obtain $m^* = 74$k€/MW/year.

Numerical illustration We describe in the following how the functions and numerical parameters were chosen. The generation costs are representative of a conventional, fossil-fired, plant. The demand distribution function(s) follow a normal distribution for simplification of the analytical resolution. The normal distribution function parameters ($\mu = 50GW$, $\sigma = 8GW$) , are rough approximations of the demand distribution in large EU countries such as France ($\mu_{FR} = 57GW$, $\sigma_{FR} = 8.5GW$ in 2024) and Germany ($\mu_{DE} = 53GW$, $\sigma_{DE} = 9.1GW$ in 2024). The price cap (P_c = 3 k€ /MWh) reflects the basic price cap applied in the EU day-ahead market [3]. The VOLL value ($VOLL$=10 k€/MWh) is an approximation considering the diversity of EU national VOLL estimates. Recent values reported in ACER monitoring report (ACER, 2025) include, for example: 7,065 €/MWh for Sweden; 12,240 €/MWh for Germany, 12,832 €/MWh for Belgium; 17,173 €/MWh for Poland; and 68,887 €/MWh for the Netherlands.

2.2 Cooperative scenario - Regional welfare

In a cooperative scenario, the two countries aim to maximize the consumers' welfare at regional level[4]. In this section, we describe the regional welfare W_R , as the sum of two components: $W_R = W_R^E + W_R^C$, where W_R^E is consumers' surplus on the energy market and W_R^C is capacity market's costs.

2.2.1 Energy market component W_R^E

Consumers' welfare on the energy market is the sum of their surplus over the various demand level conditions. When the regional demand is below the regional capacity level ($2l < k_R$), there is no curtailment, the load (l) is fully served, and the energy market price equals generators' marginal cost (C) (as reflected below in the first integral). When the regional demand exceeds the regional capacity level ($2l > k_R$), there is curtailment, only an amount k_R of load can be served, and price reach the price cap (P_c) (as reflected below in the second integral). We obtain the following consumers' welfare on the energy market:

$$W_R^E(k_R) = \int_0^{\frac{k_R}{2}} (VOLL - C)(2l)f(l)\,dl + \int_{\frac{k_R}{2}}^{\infty} (VOLL - P_c)K_R f(l)\,dl$$

Using the properties (1) (2) of the normal demand distribution function we obtain:

$$W_R^E(k_R) = 2(VOLL - C)[\mu F(\frac{k_R}{2}) - \sigma^2 f(\frac{k_R}{2})] + (VOLL - P_C)k_R[1 - F(\frac{k_R}{2})]$$

$$(\frac{\partial W_R^E}{\partial k_R}) = f(\frac{k_R}{2})\frac{k_R}{2}(P_C - C) + (1 - F(\frac{k_R}{2}))(VOLL - P_C) \qquad (6)$$

[3] At the time of writing, the maximum price cap was raised to 4000€/MWh following the energy crisis. It should be noted that the EU day-ahead price cap is dynamic. It is automatically and incrementally increased when reached for several time periods. The adjustment rule is defined in the HMMCP methodology which was updated in 2023 (ACER, 2023). Since the update, the day-ahead price cap is increased by +500€/MWh if there are two market time units of price spike over at least two days in a rolling 30 day. So, a single hour or day of scarcity would not necessarily result in a price cap change.

[4] As there is a single generation technology, generators' surplus is always equal to zero and discarded in this analysis.

2.2.2 Capacity market component W_R^C

The regional capacity costs equal the capacity price (5) multiplied by the capacity level (k_R). We obtain the following consumers' welfare on the capacity market:

$$W_R^C(k_R) = -mk_R$$

Using the properties (1) (2) of the normal demand distribution function, and the capacity price expression (5) we obtain:

$$(\frac{\partial W_R^C}{\partial k_R}) = -f(\frac{k_R}{2})\frac{k_R}{2}(P_C - C) + [1 - F(\frac{k_R}{2})](P_C - C) - (VOLL - C)[1 - F(K^*)] \quad (7)$$

2.3 Non-cooperative scenario - National welfare

In a cooperative scenario, the two countries aim to maximize the consumers' welfare at national level. In this section, we assess the national consumers welfare of country A (W_A), without loss of generality as country B is perfectly symmetrical. We describe the national consumers' welfare W_A, as the sum of two components: $W_A = W_A^E + W_A^C$, where W_A^E is consumers' surplus on the energy market, and W_A^C is the capacity market's costs.

2.3.1 Energy market component W_A^E

The value of the energy market welfare component W_A^E depends on the rule applied to allocate consumers' curtailment between the two countries. We describe this component depending on the three options introduced in 2.1: Local, Reservation, and Sharing.

Curtailment - Local With local curtailment, demand is served in priority where generation is located. As there is no transmission constraint, curtailment occurs only when the regional demand exceeds the regional capacity ($2l > k_A + k_B$). When there is no curtailment, each country has its load (l) served at the market price, which equals the marginal generation cost (C) (as reflected below in the first integrals). When curtailment occurs, the generation available is delivered in priority where it is located. We therefore have to differentiate two cases: depending on whether country A has more, or less domestic generation capacity than country B.

Let's first assume that country A has more generation capacity than country B ($k_A \geq k_B$). We note the welfare expression in such scenario W_A^{EL+}. When there is curtailment ($2l > k_A + k_B$), the energy market price reaches the market cap (P_C). If the demand in country A does not exceed the amount of capacity it has locally ($l < k_A$), there is no curtailment in country A and the demand (l) is fully served (as reflected below in the second integral). When the demand in country A exceeds its local capacity ($l > k_A$), there is curtailment and only an amount k_A of its demand is served (as reflected below in the third integral). Indeed, country B has, by construction, less generation available and no margin left to export to country A. We therefore obtain:

$$W_A^{EL+}(k_A, k_B) = \int_0^{\frac{k_A+k_B}{2}} (VOLL - C)lf(l)\, dl + \int_{\frac{k_A+k_B}{2}}^{k_A} (VOLL - P_c)lf(l)\, dl + \int_{k_A}^{\infty} (VOLL - P_c)k_A f(l)\, dl$$

Let's now assume that country A has less generation capacity than country B ($k_A < k_B$). We note the welfare expression in such scenario W_A^{EL-}. When there is curtailment ($2l > k_A + k_B$), the energy market price reaches the market cap (P_C). If the demand in country B does not exceed the amount of capacity it has locally ($l < k_B$), it can export the available excess ($k_B - l$) to country A (as reflected below in the second integral). When the demand in country B exceeds its local capacity ($l > k_B$), there is no import available for country A, and only an amount k_A of its demand is served (as reflected below in the third integral).

$$W_A^{EL-}(k_A,k_B) = \int_0^{\frac{k_A+k_B}{2}} (VOLL-C) l f(l)\, dl + \int_{\frac{k_A+k_B}{2}}^{k_B} (VOLL-P_c)(k_A+k_B-l) f(l)\, dl + \int_{k_B}^{\infty} (VOLL-P_c) k_A f(l)\, dl$$

Using the properties (1) (2) of the normal demand distribution function we obtain:

$$\begin{aligned} W_A^{EL+}(k_A,k_B) &= (P_C - C)[\mu F(\frac{k_A+k_B}{2}) - \sigma^2 f(\frac{k_A+k_B}{2})] \\ &+(VOLL - P_c)[\mu F(k_A) - \sigma^2 f(k_A) + k_A(1-F(k_A))] \end{aligned}$$

$$\begin{aligned} W_A^{EL-}(k_A,k_B) &= (VOLL - C)[\mu F(\frac{k_A+k_B}{2}) - \sigma^2 f(\frac{k_A+k_B}{2})] \\ -(VOLL - P_c)&[\mu F(k_B) - \sigma^2 f(k_B) - \mu F(\frac{k_A+k_B}{2}) + \sigma^2 f(\frac{k_A+k_B}{2})] \\ +(VOLL - P_c)&[k_A(F(k_B) - F(\frac{k_A+k_B}{2}) + k_B(1 - F(\frac{k_A+k_B}{2})] \end{aligned}$$

$$(\frac{\partial W_A^{EL+}}{\partial k_A}) = (P_c - C)\frac{1}{2}(\frac{k_A+k_B}{2}) f(\frac{k_A+k_B}{2}) + (VOLL - P_c)(1 - F(k_A)) \tag{8}$$

$$(\frac{\partial W_A^{EL-}}{\partial k_A}) = (P_c - C)\frac{1}{2}(\frac{k_A+k_B}{2}) f(\frac{k_A+k_B}{2}) + (VOLL - P_c)(1 - F(\frac{k_A+k_B}{2})) \tag{9}$$

Curtailment - Reservation With Curtailment-Reservation, demand is served to country A based on the amount of capacity it procured (noted d_A), irrespective of the procured capacity's location. We obtain the same equations as with Curtailment-Local, but the respective capacity demands (d_A, d_B) define the capacity respectively available for country A and B, instead of the local installed capacity (k_A, k_B).

$$(\frac{\partial W_A^{ER+}}{\partial d_A}) = (P_c - C)\frac{1}{2}(\frac{d_A+d_B}{2}) f(\frac{d_A+d_B}{2}) + (VOLL - P_c)(1 - F(d_A)) \tag{10}$$

$$(\frac{\partial W_A^{ER-}}{\partial d_A}) = (P_c - C)\frac{1}{2}(\frac{d_A+d_B}{2}) f(\frac{d_A+d_B}{2}) + (VOLL - P_c)(1 - F(\frac{d_A+d_B}{2})) \tag{11}$$

Curtailment - Sharing With Curtailment-Sharing, the available energy is shared equally across both countries, following a "solidarity" principle. When the regional demand does not exceed the regional capacity ($2l \leq k_A + k_B$), the market price is at the marginal generation cost (C), and the load is fully served (as reflected below in the first integral). When the regional demand exceeds the regional capacity ($2l > k_A + k_B$), curtailment occurs and the market price reaches the price cap (P_C). The curtailment is split equally between both countries irrespective of the generators' location. Half of the regional capacity ($\frac{k_A+k_B}{2}$) is therefore served in country A (as reflected below in the second integral). We therefore obtain:

$$W_A^{ES}(k_A, k_B) = \int_0^{\frac{k_A+k_B}{2}} (VOLL - C) l f(l)\, dl + \int_{\frac{k_A+k_B}{2}}^{\infty} (VOLL - P_c) \frac{k_A + k_B}{2} f(l)\, dl$$

Using the properties (1) (2) of the normal demand distribution function we obtain:

$$W_A^{ES}(k_A, k_B) = (VOLL - C)[\mu F(\frac{k_A + k_B}{2}) - \sigma^2 f(\frac{k_A + k_B}{2})] + (VOLL - P_C)\frac{k_A + k_B}{2}[1 - F(\frac{k_A + k_B}{2})]$$

$$(\frac{\partial W_A^{ES}}{\partial k_A}) = \frac{1}{2}(VOLL - C)\frac{k_A + k_B}{2} f(\frac{k_A + k_B}{2}) + \frac{1}{2}(VOLL - P_c)(1 - F(\frac{k_A + k_B}{2}) - \frac{k_A + k_B}{2} f(\frac{k_A + k_B}{2})) \tag{12}$$

We can alternatively use the capacity demand variables (d_A, d_B) instead of the local installed capacity (k_A, k_B) and we obtain the similar equation:

$$(\frac{\partial W_A^{ES}}{\partial d_A}) = \frac{1}{2}(VOLL - C)\frac{d_A + d_B}{2} f(\frac{d_A + d_B}{2}) + \frac{1}{2}(VOLL - P_c)(1 - F(\frac{d_A + d_B}{2}) - \frac{d_A + d_B}{2} f(\frac{d_A + d_B}{2})) \tag{13}$$

2.3.2 Capacity market component

The value of the capacity market component W_A^C depends on the rule applied to allocate capacity costs between the two countries. We describe this component depending on the three options introduced in 2.1: Local, Reservation, and Sharing.

Capacity costs - Local When capacity costs are allocated locally, country A pays only for the cost of domestic capacity (k_A): $W_A^{CL}(k_A, k_B) = -k_A m(k_A, k_B)$

Using the properties (1) (2) of the normal demand distribution function, and the capacity price expression (5) we obtain:

$$(\frac{\partial W_A^{CL}}{\partial k_A})(k_A, k_B) = -(P_c - C)\frac{1}{2} k_A f(\frac{k_A + k_B}{2}) - (VOLL - C)(1 - F(K^*)) + (P_C - C)(1 - F(\frac{k_A + k_B}{2})) \tag{14}$$

Capacity costs - Reservation When capacity costs are allocated based on reservation, country A pays only for the cost of capacity it has procured (d_A), irrespective of its location : $W_A^{CL}(d_A, d_B) = -d_A m(d_A, d_B)$

Using the properties (1) (2) of the normal demand distribution function, and the capacity price expression (5) we obtain:

$$(\frac{\partial W_A^{CR}}{\partial d_A})(d_A, d_B) = -(P_c - C)\frac{1}{2} d_A f(\frac{d_A + d_B}{2}) - (VOLL - C)(1 - F(K^*)) + (P_C - C)(1 - F(\frac{d_A + d_B}{2})) \tag{15}$$

Capacity costs - shared When capacity costs are shared, country A pays for half of the regional capacity ($\frac{k_A + k_B}{2}$), irrespective of the generators' location: $W_A^{CS}(k_A, k_B) = -\frac{k_A + k_B}{2} m(k_A, k_B)$

Using the properties (1) (2) of the normal demand distribution function, and the capacity price expression (5) we obtain:

$$(\frac{\partial W_A^{CS}}{\partial k_A})(k_A, k_B) = -(P_c - C)\frac{1}{2}\frac{k_A + k_B}{2} f(\frac{k_A + k_B}{2}) - (VOLL - C)\frac{1}{2}(1 - F(K^*)) + (P_c - C)\frac{1}{2}(1 - F(\frac{k_A + k_B}{2})) \tag{16}$$

We can alternatively use the capacity demand variables (d_A, d_B) instead of the domestic capacity variables (k_A, k_B). We obtain the similar derivative:

$$(\frac{\partial W_A^{CS}}{\partial d_A})(d_A, d_B) = -(P_c - C)\frac{1}{2}\frac{d_A + d_B}{2} f(\frac{d_A + d_B}{2}) - (VOLL - C)\frac{1}{2}(1 - F(K^*)) + (P_c - C)\frac{1}{2}(1 - F(\frac{d_A + d_B}{2})) \tag{17}$$

3 Results

In this section, we first show that the optimal capacity level can be achieved in a cooperative scenario (3.1). Next, we assume a non-cooperative scenario, in which policy-makers operate capacity markets to maximize their national welfare. We first show that the current regulatory set-up can result in underprocurement (3.2). Second, we verify the compatibility of alternative rules to identify potential regulatory solutions (3.3 - 3.6). An overview of the rules compatibility in a non-cooperative scenario is given in table 2 below.

Table 2 - Compatibility of capacity costs and curtailment allocation rules for the achievement of the optimal capacity level in a non-cooperative scenario

		Curtailment		
		Sharing	**Local**	**Reservation**
Costs	**Sharing**	Fully compatible	Incompatible (overprocurement)*	
	Local	Incompatible (underprocurement)	Incompatible	n.a.
	Reservation		n.a.	Fully compatible

*Note: A configuration in which capacity costs would be shared (Costs-Sharing), while curtailment would be based on domestic capacity (Curtailment-Local) or reserved capacity (Curtailment-Reservation), is considered highly unlikely. We however analyse this configuration in Appendix 4. We show that it could result in overprocurement.

3.1 The optimal regional capacity level can be achieved in a cooperative scenario

In this section, we first consider a cooperative scenario. Policymakers cooperate to maximize welfare at the regional level, rather than at national level. We show that the optimal capacity level can effectively be restored through the implementation of a regional capacity market.

Proposition 1 The equilibrium capacity in a regional cooperative scenario with a price cap and a capacity market, noted K_R^{*Coop}, is equal to the optimal equilibrium capacity in a perfect energy-only market scenario ($2K^*$).

Proof Summing the regional welfare components (6)+(7), we obtain the partial derivative relative to regional capacity (k_R):

$$(\frac{\partial W_R}{\partial k_R}) = [1 - F(\frac{k_R}{2})](VOLL - C) - [1 - F(K^*)](VOLL - C)$$

The optimal capacity is such that $\frac{\partial W_R}{\partial k_R} = 0$, which implies $F(\frac{k_R}{2}) = F(K^*)$, with F increasing over its domain. So the optimal amount of capacity in the cooperative scenario is $K_R^{*Coop} = 2K^*$.

Analysis Assuming regional cooperation, the optimum level of capacity can be achieved by the implementation of a capacity market. Policymakers pursue the maximization of welfare at regional-level, rather than at national level. This could be achieved, for example, through an integrated regional capacity market, limiting the ability of national policymakers' to influence capacity procurement.

The cooperative scenario therefore represents a first-best solution. In the next sections, we will consider that capacity markets are operated at national level. We evaluate the effect of non-cooperative behavior, where policy-makers try to maximize welfare at national-level, rather than at regional level. We verify whether the optimal capacity configurations (such that $k_A + k_B = 2K^*$) can effectively be achieved in such a non-cooperative scenario (as represented in Figure 4).

3.2 The issue: Curtailment-Sharing with national capacity markets can result in regional inadequacy

Currently, Sharing is the prevailing curtailment allocation rule in the EU, following a solidarity principle. In case of common scarcity periods, curtailment ratios are equalized, as much as physically possible, across the two countries. Moreover, capacity markets are operated at national level. Explicit cross-border participation (Cost-Reservation), or implicit cross-border participation (Cost-local) are applied. We show in this section that in such a configuration, the optimal capacity level is not a stable Nash equilibrium. We moreover illustrate with a simple numerical example the resulting inadequate capacity procurement.

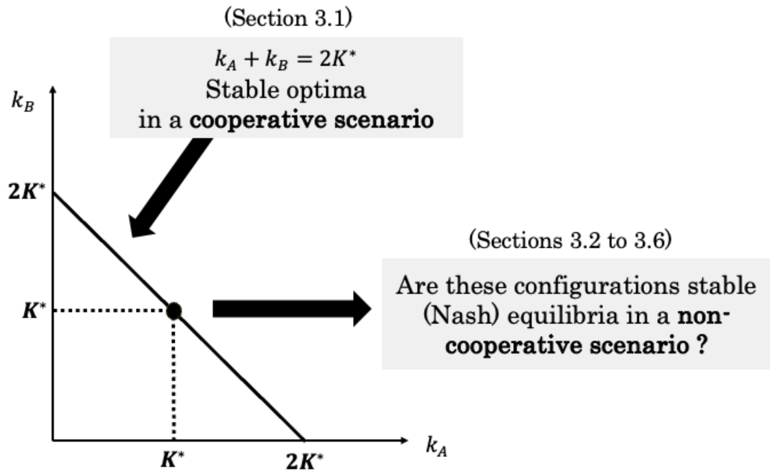

Figure 4: Analytical approach : comparing cooperative and non-cooperative equilibria alignment

Proposition 2 Combining Cost-Reservation and Curtailment-Sharing, the optimal regional capacity ($2K^*$) is not a stable Nash equilibrium in the non-cooperative scenario.

Proof Combining the welfare derivative components (13)+(15), at the symmetrical cooperative equilibrium point (d_A, d_B)=(K^*, K^*), we obtain:

$$(\frac{\partial W_A}{\partial d_A})(K^*, K^*) = -\frac{1}{2}(VOLL - P_c)(1 - F(K^*)) < 0$$

Proposition 3 Combining Cost-Local and Curtailment-Sharing, the optimal regional capacity ($2K^*$) is not a stable Nash equilibrium in the non-cooperative scenario.

Proof Combining the welfare derivative components (12)+(14), at the symmetrical cooperative equilibrium point (k_A, k_B)=(K^*, K^*), we obtain:

$$(\frac{\partial W_A}{\partial k_A})(K^*, K^*) = -\frac{1}{2}(VOLL - P_c)(1 - F(K^*)) < 0$$

Analysis When the available energy during scarcity is shared equally between the two countries, while costs are allocated based on local or reserved capacity, it is not possible to achieve the optimal regional capacity level ($2K^*$). The symmetrical optimal capacity distribution (K^*, K^*) is not a stable Nash equilibrium. Each country can individually increase its consumers' welfare by reducing its local generation capacity k_A, or capacity demand d_A. The explanation is as follows. When country A reduces its capacity demand, it proportionally reduces its capacity costs. It also sees curtailment costs increase, but not as much as in an autarky scenario, because curtailment is shared with the neighboring country B. In turn, the marginal cost savings from reducing domestic or procured capacity are higher than the additional curtailment costs. An incentive to rely on foreign generation, to "let the neighbor pay", often referred to as "free-riding behavior", therefore appears.

Proposition 4 The symmetrical national equilibrium capacity in the non-cooperative scenarios is the following: $K_{eq} = F^{-1}(1 - \frac{r}{(\frac{VOLL+P_c}{2})-C}) < K^*$

Proof Combining the welfare derivative components (12)+(14), we compute the equilibrium local capacity or capacity demand (noted k_{eq}), which verifies the non-cooperative equilibrium condition for both countries : $\frac{\partial W_A}{\partial k_A}(k_{eq}, k_{eq}) = 0$. We use the properties of the normal distribution function, in particular F admits an inverse function.

Analysis When the available energy during scarcity is shared equally between the two countries, while costs are allocated based on local or reserved capacity, we can expect under-procurement of capacity ($K_{eq} < K^*$). This is not surprising, because at the optimal capacity point (K^*, K^*), both countries can individually increase their national welfare by reducing the capacity they procure.

Numerical illustration Using the numerical values defined in section 2.2, we compute the relative deviation from the optimal equilibrium capacity, loss of load expectation, energy not served, the absolute welfare deviations.

Table 3 - Numerical illustration of the risk of capacity underprocurement assuming Curtailment-Sharing and Costs-Local or Costs-Reservation .

Cost allocation Curtailment allocation	Local/Reservation Sharing
Relative capacity deviation	−1.4%
Relative LOLE deviation	+54%
Relative ENS deviation	+60%
Relative capacity costs deviation	−23%
Absolute energy market surplus deviation	−2691 M€/year
Absolute capacity costs (savings) deviation	+2634 M€/year
Absolute welfare deviation	−57 M€/year

When curtailment is shared, and capacity costs are allocated based on domestic or procured capacity, we can expect an underprocurent of around −1.4% of capacity. Though this relative change appears quite low, it increases the loss of load expectation by +54% and unserved energy by +60%[5]. As generators' scarcity revenues increase, the capacity costs conversely decrease, by around −23%. At regional level, the resulting absolute welfare loss reaches −57 M€/year.

3.3 Local-priority curtailment cannot enable effective capacity procurement either

We have shown that the national operation of capacity markets is incompatible with Curtailment-Sharing. A solution could be to implement Curtailment-Local. In such a scenario, the available generation goes in priority to the country where the underlying capacity is physically located. This corresponds to minimizing cross-border flows. Such scenario is realistic in the EU: TSOs can be

[5] In this model, we assume that national policy-makers' objective is to maximize domestic surplus. One could assume instead the objective to be containing LOLE or ENS below a given target. In such a scenario, the risk of under-procurement could be more limited. It all depends on how the given target is defined. For example, if the Reliability Standard (LOLE target) is optimally set considering the Cost and Curtailment rules in place, then we expect that both scenarios would align.

tempted, or pushed politically by national interest groups, to limit the cross-border capacity available for trade when anticipating reliability issues. In this section, we show that such a configuration can result in inefficient capacity procurement. In other words, allocating both the costs and the benefits of capacity markets at national level can lead a suboptimal capacity procurement at regional level.

Proposition 5 Combining Cost-Local and Curtailment-Local, none of the optimal capacity distributions (such that $k_A + k_B = 2K^*$) is a stable Nash equilibrium in the non-cooperative scenario, except for the symmetrical distribution (K^*, K^*).

Proof We combine the welfare derivative components (9)+(14) or (8)+(14). At a cooperative equilibrium point (k_A, k_B) such that $k_A + k_B = 2K^*$, we obtain:

If $k_A > k_B$: $\frac{\partial W_A}{\partial k_A} = f(K^*)\frac{1}{2}(P_C - C)(K^* - k_A) + [F(K^*) - F(k_A)](VOLL - P_C) < 0$

If $k_A = k_B$: $\frac{\partial W_A}{\partial k_A} = 0$

If $k_A < k_B$: $\frac{\partial W_A}{\partial k_A} = f(K^*)\frac{1}{2}(P_C - C)(K^* - k_A) + [F(K^*) - F(K_A)](VOLL - C) > 0$

For any cooperative equilibrium point (k_A, k_B) such that $k_A \neq k_B$, we have $\frac{\partial W_A}{\partial k_A}(k_A, k_B) \neq 0$, so (k_A, k_B) is not a non-cooperative equilibrium point. Only the symmetrical cooperative equilibrium point (K^*, K^*) is also a non-cooperative equilibrium.

Proposition 6 Assuming asymmetrical investment costs ($r_A < r_B$), combining Cost-Local and Curtailment-Local, the unique optimal capacity distribution $(2K^*, 0)$ is not a stable Nash equilibrium in the non-cooperative scenario.

Proof Proof is provided in Appendix 1.

Analysis When both capacity costs and curtailment are allocated based on domestic capacity, it is only possible to achieve the optimal regional capacity level if capacity is symmetrically distributed across the two countries. The explanation is the following. If country A procures more than the equilibrium capacity, savings in curtailment costs are smaller than the additional capacity costs incurred. Vice-versa, if country A procures less than the equilibrium capacity, the additional curtailment costs incurred are bigger than the capacity costs savings. As a result, only the symmetrical distribution (K^*, K^*) is a stable equilibrium. One could rightfully argue that these rules can therefore be compatible, as the optimal regional capacity level $(2K^*)$ is achievable. However, assuming non-symmetrical investment costs, the "local" allocation of curtailment and capacity costs makes the regional optimum non achievable (see Appendix 1). This is because, assuming local cost allocation in the optimal capacity distribution $(2K^*, 0)$, country A would have to bear the costs of capacity procurement for the whole region.

3.4 Solution 1: Allow for an effective reservation of foreign capacity for delivery during scarcity

The issue identified in section 3.2 arises from the incompatibility between Curtailment-Sharing and Costs-Reservation. An alternative to Curtailment-Sharing is Curtailment-Reservation. In case of simultaneous scarcity, cross-border flows could be defined based on each country's capacity procurement. In this section, we show that such configuration does enable adequate capacity procurement in a non-cooperative scenario. This therefore represents a first solution to the risk of non-cooperative behavior between national capacity markets.

Proposition 7 Combining Cost-Reservation and Curtailment-reservation, any optimal capacity capacity distribution (such that $k_A = k_B = 2K^*$) is a stable Nash equilibrium the non-cooperative scenario.

Proof We combine the welfare derivative components (10)+(15) or (11)+(15). At any cooperative equilibrium point (d_A, d_B) such that $d_A + d_B = k_A + k_B = 2K^*$, we obtain:

If $d_A > d_B$: $\frac{\partial W_A}{\partial d_A} = f(K^*)\frac{1}{2}(P_C - C)(K^* - d_A) + [F(K^*) - F(d_A)](VOLL - P_C) < 0$

If $d_A = d_B$: $\frac{\partial W_A}{\partial d_A} = 0$

If $d_A < d_B$: $\frac{\partial W_A}{\partial d_A} = f(K^*)\frac{1}{2}(P_C - C)(K^* - d_A) + [F(K^*) - F(d_A)](VOLL - C) > 0$

At an equilibrium point, the capacity demands must be equally shared in both countries ($d_A = d_B = K^*$). As the demands are not linked to the generators' location, any optimum generators' distribution (k_A, k_B, such that $k_A + k_B = 2K^*$) is a stable equilibrium in the non-cooperative scenario.

Analysis When both capacity costs and curtailment are allocated based on the capacity each country has procured, any optimal regional capacity distribution can be achieved in a non-cooperative scenario. At equilibrium, the two country's capacity demand are symmetrical ($d_A = d_B = K^*$). The explanation is as follows. If country A procures more than the equilibrium capacity, the additional capacity costs will be higher than the curtailment costs savings. Vice-versa, if country A procures less than the equilibrium capacity, the additional curtailment costs will be higher than the capacity costs savings. More concretely, each country pays exactly for the capacity which it will get during scarcity. These rules are compatible precisely for this reason: the benefits of procuring capacity (reduced curtailment) are directly linked to its costs. This ensures that no country has an incentive to under- or over- procure capacity. Moreover, compared to Local-based rules (discussed in 3.3), Reservation-based rules allow to disconnect the capacity procured from its geographical location. This effectively incentivizes procurement of capacity where it is the cheapest (see Appendix 1).

3.5 Solution 2: Share both curtailment and capacity costs

The issue identified in section 3.2 arises from the incompatibility between Curtailment-Sharing and Costs-Reservation. An alternative to Costs-Reservation is Cost-Sharing. In such scenario, solidarity would still apply during common scarcity situations. The cost of capacity procurement would be shared accordingly, i.e. proportional to each country's supplied demand during the common regional peak. In this section, we show that such configuration does enable adequate capacity procurement in a non-cooperative scenario. This therefore represents a second solution to the risk of non-cooperative behavior between national capacity markets.

Proposition 8 Combining Cost-Sharing and Curtailment-Sharing, any optimal capacity distribution (such that $k_A = k_B = 2K^*$) is a stable Nash equilibrium the non-cooperative scenario.

Proof We combine the welfare derivative components (12)+(16). At any point (k_A, k_B), we obtain:

$$\frac{\partial W_A}{\partial k_A}(k_A, k_B) = \frac{1}{2}(VOLL - C)[F(K^*) - F(\frac{k_A + k_B}{2})]$$

At a cooperative equilibrium point (such that $k_A + k_B = 2K^*$), we obtain: $\frac{\partial W_A}{\partial k_A} = 0$

Analysis When both curtailment and capacity costs are shared between the two countries, any optimal capacity distribution (k_A, k_B verifying $k_A + k_B = 2K^*$) is a achievable in the non-cooperative scenario. Country A cannot increase its national welfare by modifying unilaterally its local capacity level (or capacity demand). This is because the national welfare is a function of the regional capacity level and does not depend on the distribution of that capacity between the two countries. This is not surprising, as a scenario in which both costs and curtailment are shared is, de facto, a cooperative scenario. This solution therefore resembles the cooperative scenario (section 3.1), which could be implemented through an integrated regional capacity market.

3.6 Solution 3: Keep the current framework, but define ad-hoc cross-border compensations

We have shown in section 3.2 that the current EU framework, combining Curtailment-Sharing and Cost-Reservation cannot enable adequate capacity procurement. If the current framework is maintained, an intermediate solution is to define ad-hoc cross-border compensations. The objective is to fairly share capacity costs, considering solidarity in curtailment allocation. In this section, we define the ad-hoc compensations necessary to restore appropriate capacity procurement incentives.

Proposition 9 Assuming Cost-Reservation and Curtailment-Sharing, the compensation from country B to A (or respectively from A to B if negative), noted $P_{B->A}$, needed to restore appropriate capacity procurement incentives is the following:

$$P_{B->A} = \frac{d_A - d_B}{2} m$$

Proof We have shown in 3.4 that Curtailment-Sharing is compatible with Costs-Sharing. To restore adequate capacity procurement assuming Curtailment-Sharing, ad-hoc payments should therefore result ad-hoc in Costs-Sharing. $P_{B->A}$ is the difference between the Capacity cost Welfare component in the Cost-Sharing and Cost-Reservation scenarios $P_{B->A} = W_A^{CS} - W_A^{CR}$.

Analysis Assuming Curtailment-Sharing, both countries benefit equally from an additional capacity built in the region. Because there is no transmission constraint, they both get half of the additional generation available during scarcity. If country A procures more than country B, it should therefore be compensated by country B for half of this additional procurement ($\frac{d_A - d_B}{2}$). Such payments result in moving, ex-post, from Cost-Reservation towards Cost-Sharing.

4 Practical implementation challenges

Currently, capacity markets are operated at national level, which can result in inadequate capacity procurement due to non-cooperative behavior. Curtailment-Sharing and Costs-Reservation are the prevailing rules. We have shown in Section 3.2, that such configuration can result in underprocurement of capacity at regional level. We moreover identified potential theoretical solutions (see table 2). In this section, we discuss qualitatively the challenges that would arise in implementing such solutions in the EU.

Table 2 - Overview of regulatory solutions

<table>
<tr><th></th><th></th><th colspan="3">Curtailment</th></tr>
<tr><th></th><th></th><th>Sharing</th><th>Local</th><th>Reservation</th></tr>
<tr><th rowspan="3">Costs</th><th>Sharing</th><td>Solution 2
Regional capacity market</td><td colspan="2">(non realistic scenario)</td></tr>
<tr><th>Local</th><td rowspan="2">Solution 3
Ad-hoc cross-border compensations</td><td>Incompatible</td><td>n.a.</td></tr>
<tr><th>Reservation</th><td>n.a.</td><td>Solution 1
Reservation based curtailment allocation</td></tr>
</table>

Ad-hoc cross-border compensations First, assuming the current regulatory framework is maintained, cross-border compensations could be defined (Solution 3). The objective of such compensations would be to fairly allocate the cost of capacity procurement, based on the benefits of the adequacy measures observed at regional level. The methodology for computing compensations could be defined ex-ante. Their amount could then be computed ex-post, based on the actual curtailment observed during common scarcity situations. Establishing such a methodology for cross-border compensations might be challenging in practice, considering constraints on interconnectors, on the internal transmission networks, and the presence of non-simultaneous scarcity events. However, it would translate into a fair allocation of capacity costs across Europe.

Reservation based curtailment allocation Second, curtailment rules could be changed in the day-ahead algorithm (Solution 1). During simultaneous scarcity events, the available generation could be directed towards the country which procured it. Say country A has procured 1GW of capacity in country B, while country B has not procured any capacity in country A. The "last resort" rule in the day-ahead market algorithm EUPHEMIA (i.e. defining cross-border flows when the price cap is reached in the region) would allocate 1GW of exports from country B to country A, rather than equalizing the curtailment ratios in the two countries. However, such a solution might not be so straightforward to implement in practice. The application of "curtailment-sharing" in EUPHEMIA, also referred to the "adequacy patch", is needed to ensure a fair allocation of energy not served considering the effects of flow factor competition introduced by flow-based market coupling, as explained by Elia (2022). Moreover, article 194 of TFEU enshrined the principle of "solidarity between Member States" in law, and in particular for measures related to security of energy supply.[6]. "Curtailment-sharing" in EUPHEMIA represents an automatic solidarity measure, and one could argue that moving away from Curtailment-sharing contradicts the legal solidarity principle.

[6] See, for example the "OPAL case" (C-848/19 P, Germany against Poland). The Court of Justice concluded "The legality of any act of the EU institutions falling within the European Union's energy policy must be assessed in the light of the principle of energy solidarity".

Regional capacity market Third, the capacity costs could be shared (Solution 2). The solidarity principle would still apply during scarcity situations. To align with Curtailment-Sharing, the costs of capacity procurement would also be shared at regional level already ex-ante, based on each Member States expected demand during common scarcity situations. Sharing both costs and curtailment would ensure that policy-makers have an incentive to maximize welfare at the regional level, as this would also maximize their welfare at national level. The sensitive assumption in such a scenario is trusting Member States to, in fact, apply Curtailment-sharing during common scarcity periods. To limit incentives to restrict exports, a cost correction rule could additionally apply ex post, such that Member States do in fact pay for the right share of the regionally procured capacity (similar to solution 3). This solution would entail a stronger coordination, or ideally, the integration of capacity markets at regional level. Prerequisites to a regional capacity market include products' harmonisation, design convergence, and development of capacity market coupling rules, raising numerous challenges. We consider, however, this solution to be ideal for the medium to long term. In Menegatti & Meeus (2025), we explore in more details why and how to move from national to regional capacity markets in the EU.

5 Model limitations

In this section, we first discuss the limitations of our modelling approach. Second, we discuss the applicability of our results and conclusions.

First, our model is deliberately stylized, and far from the complexity of EU interconnected electricity systems. We argue that our approach is an "argument from the simplest case". Market rules should show efficient outcomes, a fortiori, in the simplest setting. If market rules do not deliver efficient outcomes in the simplest setting, we can expect that they would also show limitations in a more complex setting. However, additional insights can be derived by relaxing our strict assumptions. In the paragraphs below, we discuss our main assumptions, and the possibilities to extend our model with alternative market configurations.

Supply side assumptions A crucial simplifying assumption in our core model is the perfect symmetry of technology costs. Where technology costs differ, we can expect to see additional incentives for countries to procure generation capacity abroad, if the latter is cheaper. In Appendix 1, we discuss the case of heterogeneous investment costs. In such a scenario, all generation capacity should be located in the cheaper country to minimize the regional system costs. This asymmetrical capacity distribution cannot be achieved when costs are allocated based on domestic capacity, as the cheaper country would have to bear the costs of capacity procurement for the entire region. The optimum can however be achieved with when costs and curtailment are both shared, or are both allocated based on capacity reservation. Our approach could be extended in future research to explore, for example the case of : n >1 generating technologies, or continuous supply curve functions. In such settings, the generators' surplus should additionally be considered in the welfare expression.

Demand side assumptions A crucial assumption in our core model is the perfect symmetry of the national demands. This symmetry means that scarcity events are always simultaneous. In practice, national electricity demands are not perfectly correlated, and scarcity periods can be non simultaneous. In Appendix 2, we generalize our core proposition (3 - incompatibility of Curtailment-sharing and Costs-local) for two non-perfectly correlated national demands with correlation parameter ρ. We find that capacity deviation in the non-cooperative scenario increases with demand correlation. Our analytical approach could be extended in future research to explore, for example: equilibrium conditions assuming heterogeneous VOLL, normal demand distribution functions with non symmetrical means and variance, and fat-tail or other alternative demand distributions.

Transmission capacity assumption For simplification purposes, we have chosen to ignore transmission constraints in our core model. In practice, cross-border interconnectors have a maximum capacity which is likely to be reached, especially during scarcity periods. However, we show in Appendix 3 that our main proposition (3 - incompatibility of Curtailment-sharing and costs-local) can be generalized to the case where interconnection capacity is limited. Indeed, assuming perfectly correlated electricity demands, transmission capacity is binding during scarcity events only if there is an important capacity asymmetry between the two countries. In such a case, both countries have an incentive to reduce or increase capacity payments to restore symmetry (one to reduce curtailment, the other to reduce capacity costs). When the capacity distribution is more balanced, the interconnector is no longer binding during scarcity and our core results apply. Our model could be extended to explore the effect of transmission constraints in the case of non perfectly symmetrical demands.

Market failure A capacity market can increase welfare only in the presence of a market failure which results in under-investments in the energy-only scenario. To simplify our analysis, we have chosen to represent the market failure as an explicit price cap on wholesale energy prices. In practice, price caps on the EU SPOT markets are dynamic, in order to allow for scarcity prices to materialize. The explicit price cap we model can also be considered a proxy for an implicit price cap. An implicit price cap is realistic assuming retailers' risk-taking behavior (i.e. bidding below optimal), or other imperfections in the scarcity price formation resulting from the lack of information on consumers valuation of continued electricity supply.

Second, our results hint that the current EU market setting could result in under-procurement. We acknowledge that, considering the political aversion to consumers' curtailment, under-procurement is in practice less likely. However, what we show with our simple model is a misalignment between the adequacy framework and the short-term curtailment rules. Explicit cross-border participation, i.e. paying for capacity abroad, does not make sense if that capacity is not effectively reserved, i.e. delivered in priority to the country that procured it during scarcity. In case of simultaneous scarcity, consumers might eventually not benefit from the service they paid for. As a result, policy-makers, and system operators, have no reason or incentive to implement explicit cross-border participation.

6 Conclusions

In this paper, we have explored different options to allocate the costs (capacity payments) and the benefits (reduced curtailment) of national resource adequacy policies. Our main finding is that the framework for national capacity markets is not aligned with the short-term curtailment allocation rules. If "curtailment sharing" applies in case of simultaneous scarcity situations, Member States cannot effectively reserve the capacity they pay for. This results, first, in an incentive to underprocure capacity ("free-riding"), and second, in a disinterest in implementing explicit cross-border participation.

We moreover identified three main solutions to this misalignment. First, the current framework could be maintained, but ad-hoc cross-border compensations would be allocated, resulting de facto in sharing capacity costs. Second, curtailment rules could be modified. In case of simultaneous scarcity, cross-border flows would be defined based on each country's capacity procurement, rather than curtailment sharing. This, however, implies renouncing to cross-border solidarity during scarcity periods. These first two options appear difficult to implement in the EU, and not ideal for the long term. Third, capacity costs could be shared through a regional capacity market. This last option might be challenging in the short term, raising numerous technical and implementation questions. However, we argue that a regional or European approach is increasingly needed, considering rising levels of interconnectivity, and the growing perimeter of national capacity markets.

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8 Appendix

In our core model, we have made a number of simplifying assumptions. In this appendix, we relax a number of these assumption to extend or complement our main results. First, we consider asymmetry in the national technology investment costs (8.1), to complement our core conclusions. Second, we consider non perfectly correlated national electricity demands (8.2), to generalize proposition 3. Third, we consider a binding interconnector (8.3), to generalize proposition 3. Finally, we consider the unlikely combination of "cost sharing" with local or procurement based curtailment rules (8.4), which enables us to complete Table 2.

8.1 What if technology costs are non symmetrical?

In our core model, we have assumed equal investment costs in zone A and B ($r_A = r_B = r$). In this section, we assume non symmetrical investment costs. As in Section 3, we verify whether the optimum capacity distribution is feasible in a non-cooperative scenario. Without loss of generality, we assume costs to be lower in country A, than in country B: $r_A < r_B$.

8.1.1 Changes in the model set-up

Regional optimal capacity When $r_A < r_B$, the only optimal capacity distribution is $k_A = 2K^*$, $k_B = 0$. In the following, we will therefore test whether $(2K^*, 0)$ is a stable Nash equilibrium.

Capacity market With heterogeneous investment costs, to equalize investment incentives in the two countries we must have the following capacity payments: $(m_A, m_B) = (r_A - (P_C - C)(1 - F(K_R)), r_B - (P_C - C)(1 - F(K_R))$, which imposes $m_A \neq m_B$.

8.1.2 Changes in the welfare components

Regional welfare - Capacity market component The capacity market regional welfare component now depends on the generators' location:

$$W_R^C(k_A, k_B) = -m_A k_A - m_B k_B = -m_A k_A - (m_A + r_B - r_A) k_B$$

We note K^* the equilibrium capacity corresponding to A in autarky, i.e. such that $r_A = (VOLL - C)(1 - F(K^*))$. We moreover note $\Delta r = r_B - r_A (> 0)$. The capacity market welfare becomes:

$$W_R^C(k_A, k_B) = -[(VOLL - C)(1 - F(K^*)) - (P_C - C)(1 - F(\frac{k_A + k_B}{2}))](k_A + k_B) - (\Delta r)k_B$$

National welfare - Capacity market component - Costs-Reservation As the capacity payments needed in A and B become asymmetrical, we must introduce additional variables describing how the capacity demands are split regionally. Variable d_{A-A}, d_{A-B} describe the capacity demand of country A for generators respectively located in country A, and in country B. We have $d_A = d_{A-A} + d_{A-B}$. Similarly, we have $d_B = d_{B-A} + d_{B-B}$. We obtain $W_A^{CR} = -m_A d_{A-A} - m_B d_{A-B}$. Symmetrically, for country B, $W_B^{CR} = -m_A d_{B-A} - m_B d_{B-B}$.

8.1.3 Results

Cooperative scenario (extension of section 3.1)

Proposition When investment costs are are lower in country A ($r_A < r_B$), the only stable equilibrium capacity distribution is equal to the optimal equilibrium capacity distribution in a perfect energy-only scenario $(k_A, k_B) = (2K^*, 0)$.

Proof We sum the regional welfare component on the energy market W_R^E (unchanged, see 2.3), and capacity market component W_R^C (described above) as a function of the two variables (k_A, k_B) :

We obtain the following equilibrium conditions:

$$\begin{cases} \frac{\partial W_R}{\partial k_A} = (VOLL - C)[(F(K^*) - F(\frac{k_A + k_B}{2})] = 0 \text{ or } k_A = 0 \\ \frac{\partial W_R}{\partial k_B} = (VOLL - C)[(F(K^*) - F(\frac{k_A + k_B}{2}) - \Delta r] = 0 \text{ or } k_B = 0 \end{cases}$$

There are only two solutions: $(k_A, k_B) = (0, 2K^*)$ or $(k_A, k_B) = (2K^*, 0)$. We have $W_R^E(2K^*, 0) - W_R^E(0, 2K^*) = 2K^*(\Delta r) > 0$. So, the optimal capacity distribution is $k_A = 2K^*, k_B = 0$.

Costs-Local and Curtailment-Local (extension of Section 3.3)

Proposition Combining Costs-Local and Curtailment-Local, the optimal regional capacity distribution $(2K^*, 0)$ is not stable in a non-cooperative scenario.

Proof We assume that country A has more generation capacity than country B (as it should be in the optimal configuration). Combining the welfare derivative components (14)+(8), we obtain the following welfare derivative for country A :

$$(\frac{\partial W_A}{\partial k_A}) = (P_c - C)f(\frac{k_A + k_B}{2})\frac{1}{2}(\frac{k_B - k_A}{2}) + (VOLL - C)(F(K^*) - F(\frac{k_A + k_B}{2}))$$

At the regional optimum such that all generation capacity is located in A ($k_A = 2K^*$) we obtain

$$(\frac{\partial W_A}{\partial k_A})(2K^*, 0) = -(P_c - C)f(K^*)\frac{1}{2}(K^*) < 0$$

Analysis When investment costs are considered lower in country A, and without any transmission constraint, it is economically optimal to place all generation in country A ($k_A = 2K^*, k_B = 0$). However, assuming a local allocation of capacity costs and curtailment, such configuration is not a stable equilibrium in the non-cooperative scenario. Country A can increase its welfare by reducing domestic capacity. The explanation is as follows. If country A hosts the entire regional capacity, and the costs are allocated locally, consumers in country A end up bearing the entire cost of the adequacy policy. They pay twice as much as they would in an autarky scenario. They also benefit from reduced curtailment costs, but not that much, because there is domestic overcapacity. In summary, if country A hosts less domestic capacity, it would save more in capacity costs, than it would lose in curtailment costs. The local allocation of capacity costs creates a preference for foreign capacity, to "let the neighbor pay", which is problematic when national costs differ.

Costs-Reservation and Curtailment-Reservation (extension of Section 3.4)

Proposition Combining Cost-Reservation and Curtailment-Reservation, the optimal regional capacity distribution $(2K^*, 0)$ is stable in a non-cooperative scenario.

Proof We sum the energy market welfare component (unchanged, see section 2.4), and the capacity market component (described above).

We check the feasibility of the unique optimum regional configuration such that : the regional capacity demand is equal to the optimum ($d_A + d_B = 2K^*$), and everything is located in country A ($d_{A-B} = d_{B-B} = 0$). We additionally inject the condition imposing equally shared capacity demands ($d_{A-A} = d_{B-A} = K^*$).

We obtain :

$$(\frac{\partial W_B^{ER}}{\partial d_{A-A}}) = (\frac{\partial W_B^{ER}}{\partial d_{A-B}}) = (\frac{\partial W_A^{ER+}}{\partial d_{A-A}}) = (\frac{\partial W_A^{ER+}}{\partial d_{A-B}}) = (P_c - C)\frac{1}{2}(K^*)f(K^*) + (VOLL - P_c)(1 - F(K^*))$$

And:

$$(\frac{\partial W_A^{CR}}{\partial d_{A-A}}) = (\frac{\partial W_B^{CR}}{\partial d_{B-A}}) = -(P_c - C)\frac{1}{2}K^* f(K^*) - (VOLL - C)(1 - F(K^*)) + (P_C - C)(1 - F(K^*))$$

$$(\frac{\partial W_A^{CR}}{\partial d_{A-B}}) = (\frac{\partial W_B^{CR}}{\partial d_{B-B}}) = -(P_c - C)\frac{1}{2}K^* f(K^*) - (VOLL - C)(1 - F(K^*)) + (P_C - C)(1 - F(K^*)) - \Delta r$$

Combining the components computed for the proposed solution, we obtain :

$$(\frac{\partial W_A}{\partial d_{A-A}}) = (\frac{\partial W_B}{\partial d_{B-A}}) = 0$$

$$(\frac{\partial W_A}{\partial d_{A-B}}) = (\frac{\partial W_B}{\partial d_{B-B}}) = -\Delta r < 0$$

As $d_{A-B} = d_{B-B} = 0$, the constraint is binding and explains the second inequality. The stability of the solution is therefore verified.

Analysis This result extends the compatibility of Curtailment-Reservation with Costs-Reservation established in section 3.4. The cost of the capacity procured is effectively linked to its availability during scarcity, and de-linked from its location. Both countries have an incentive to procure capacity where it is the cheapest, in country A, to reduce the procurement costs. This is only possible if country B is ensured to effectively access the generation capacity procured in country B during scarcity.

Costs-Sharing and Curtailment-Sharing (extension of Section 3.5)

Proposition Combining Cost-sharing and Curtailment-Sharing, the optimal regional capacity distribution $(2K^{*}, 0)$ is stable in a non-cooperative scenario.

Proof When both costs and curtailment are shared, the national welfare components (non-cooperative scenario) are exactly half of the regional welfare component (in a cooperative scenario). As proved above, the solution $(2K^{*}, 0)$ maximizes the regional welfare, and therefore also maximizes the national welfare in such scenario.

Analysis This result extends the compatibility of Curtailment-Sharing with Costs-Sharing established in section 3.2.3.a. Sharing both costs and curtailment is de facto a cooperative scenario. Both countries have incentives to maximize welfare at regional level, to maximize their own national welfare.

8.2 What if the demands are not perfectly correlated?

One of our core assumption is the prefect symmetry and correlatio between the national electricity demands (at any point in time, $l_A = l_B = l$). This assumption magnifies the occurrence of simultaneous scarcity events across the two countries. In this section, we assume symmetry between the demand distribution functions (equal mean and variance) but with imperfect correlation. We focus on verifying our core proposition (3, incompatibility between Curtailment-sharing and Costs-local).

8.2.1 Changes in the model set-up

Electricity demand

We introduce parameter ρ which represents the correlation between the two demands. The regional-level demand definition ($l_R : l_A + l_B$) a linear combination of two normally distributed, non-independent variables. They follow a Gaussian or joint normal distribution of function $f_{corr}(l_R = l_A + l_B)$ of mean $\mu_{corr} = 2\mu$, standard deviation $\sigma^2_{corr} = 2\sigma^2(1+\rho)$, and integral function noted F_{corr}. We use the same properties of the normal distribution function as in Section 2.

We additionally use the properties of multivariate Gaussian distribution functions, in particular, the probability density function of vector (l_A, l_B) is :

$$f(l_A, l_B) = \frac{1}{2\pi\sigma^2\sqrt{(1-\rho^2)}} * exp(-\frac{1}{2[1-\rho^2]}[(\frac{l_A-\mu}{\sigma})^2 + (\frac{l_B-\mu}{\sigma})^2 - 2\rho(\frac{(l_A-\mu)(l_B-\mu)}{\sigma^2})]$$

Regional optimal capacity Taking similar steps as in section 2.1, we can compute the equilibrium regional capacity in the perfect energy only scenario $K_R^{*corr} = F^{-1}_{corr}(1 - \frac{r}{VOLL-C})$,

Capacity market Considering the price cap P_C, the capacity payments necessary to restore the optimum amount of capacity become $m^{*corr} = (VOLL - P_C)(1 - F_{corr}(K_R^{*corr}))$.

8.2.2 Changes in the welfare components

National welfare - Energy market - Curtailment sharing

Assuming curtailment sharing, the energy market component for country A becomes:

$$W_A^{EScorr} = (VOLL - C)I_1 + (VOLL - P_C)k_R I_2$$

with I_1 the welfare integral when the load is fully served:

$$I_1 = \int_{l_B=0}^{\infty} \int_{l_A=0}^{k_R - l_B} l_A f(l_A, l_B) dl_A dl_B$$

and I_2 the welfare when the load cannot be fully served, and energy is shared following the "curtailment sharing" principle:

$$I_2 = \int_{l_B=0}^{\infty} \int_{l_A=k_R-l_B}^{\infty} \frac{l_A}{l_B + l_A} f(l_A, l_B) dl_A dl_B$$

Let's first consider I_1. According to the law of total expectations, we have:

$$I_1 = \mathbb{E}[l_A 1_{l_R < k_R}] = \int_{l_R=0}^{K_R} \mathbb{E}[l_A \mid l_A + l_B = l_R] f_R(l_R) dl_R$$

We recall that (l_A, l_B) is jointly normal with equal means and variance. By the linear conditional expectation property of jointly normal random variables, we have:

$$\mathbb{E}[l_A \mid l_A + l_B = l_R] = \frac{Cov(l_A, l_A + l_B)}{Var(l_A + l_B)}(l_R - \mu_R) + \mu = \frac{\sigma^2(1+\rho)}{2\sigma^2(1+\rho)}(l_R - 2\mu) + \mu = \frac{l_R}{2}$$

Hence, $I_1 = \int_{l_R}^{K_R} \frac{l_R}{2} f_R(l_R) dl_R = \frac{1}{2}(\mu_R F_R(k_R) - \sigma_R^2 f_R(k_R))$

Now let's consider the second integral: $I_2 = \mathbb{E}[\frac{l_A}{l_A + l_B} \mathbb{1}(l_A + l_B \geq K_R)]$. According to the laws of iterated expectations $I_2 = \mathbb{E}[\mathbb{E}[\frac{l_A}{l_R} \mathbb{1}(l_R \geq K_R) \mid l_R]]$. Because l_A, l_B are jointly normal and with the same distribution, we have $\mathbb{E}[l_A \mid l_R] = \frac{l_R}{2}$. So, $I_2 = \mathbb{E}[\frac{1}{2}\mathbb{1}(l_R \geq K_R)]$. We therefore obtain:

$$I_2 = \frac{1}{2}[1 - F_{corr}(k_R)]$$

and combining the elements:

$$W_A^{EScorr} = (VOLL - C)[\frac{1}{2}(\mu_R F_{corr}(k_R) - \sigma_R^2 f_{corr}(k_R))] + (VOLL - P_C)k_R \frac{1}{2}[1 - F_{corr}(k_R)]$$

$$\frac{\partial W_A^{EScorr}}{\partial k_A} = \frac{\partial W_A^{EScorr}}{\partial k_R} = \frac{(VOLL - C)}{2} k_R f_{corr}(k_R) + \frac{(VOLL - P_C)}{2} [1 - F_{corr}(k_R) - K_R f_{corr}(k_R)]$$

We obtain a similar expression as we did with the symmetrical and perfectly correlated demands (equation 12), but with the covariate distribution function f_R of parameters μ_{corr}, σ_{corr}. This generalizes our result with perfectly correlated demands which can be obtained assuming $\rho = 1$.

National welfare - Capacity market - Costs local

Assuming costs-local, the capacity market component of the welfare is the following: $W_A^{CLcorr} = k_A m_{corr}(k_R)$ with the capacity price component determined by the perfect competition assumption:

$$m_{corr}(k_R) = (VOLL - C)(1 - F_{corr}(k_R^{*corr})) - (P_C - C)(1 - F_{corr}(k_R))$$

Hence we obtain :

$$\frac{\partial W_A^{CLcorr}}{\partial k_A} = -(P_C - C) k_A f(k_R) - (VOLL - C)(1 - F(K_R^{*corr})) + (P_C - C)(1 - F(k_R))$$

8.2.3 Results

Curtailment Sharing and Costs Local (extension of Section 3.2)

Proposition Combining Cost-local and Curtailment-Sharing, with non perfectly correlated demands, the optimal regional capacity K_R^{*corr} is not a stable Nash equilibrium in the non-cooperative scenario.

Proof Combining the welfare derivative components, at the symmetrical equilibrium point $(k_A,k_B)=(\frac{K_R^{*corr}}{2}, \frac{K_R^{*corr}}{2})$, we obtain:

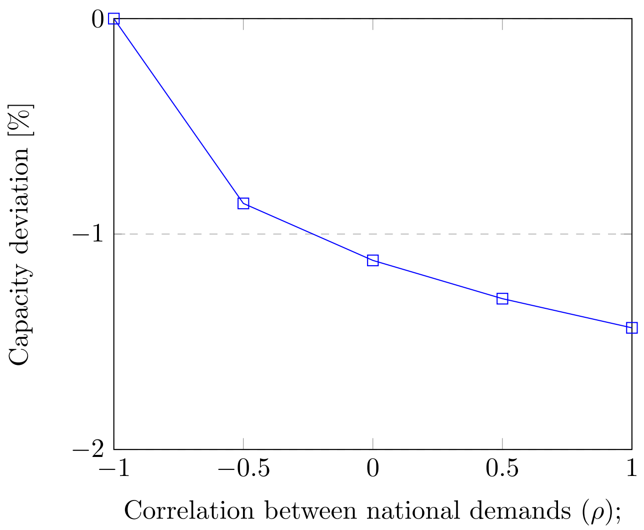
$$\frac{\partial W_A^{corr}}{\partial K_A} = -\frac{1}{2}(VOLL - P_C)(1 - F_{corr}(K_R^{*corr})) < 0$$

Proposition The symmetrical national equilibrium capacity in the non-cooperative scenario is the following: $K_{eq}^{*corr} = \frac{1}{2} F_{corr}^{-1}(1 - \frac{r}{(\frac{VOLL+P_c}{2}) - C}) < \frac{1}{2} K_R^{*corr}$.

Proof Combining the welfare derivative components, we compute the equilibrium local capacity (noted K_{eq}^{*corr}) which verifies the non-cooperative equilibrium condition for both countries: $\frac{\partial W_A^{corr}}{\partial K_A} = 0$

Numerical illustration We compute the equilibrium capacity deviation for different values of the correlation parameter ρ.

Figure 1 - Capacity deviation (Y axis, %) in the non-cooperative scenario relative to the optimal cooperative scenario, for different demand correlations (X axis)



The capacity deviation increases with the correlation of demands. As the occurence of simultaneous scarcity events increases, building - and paying for - more domestic capacity also means sharing more that capacity with the neighbor. Therefore, the incentive to underprocure increases with the correlation of demands.

8.3 What if the interconnector is binding?

In our core model, we have assumed the interconnector not binding. In practice, interconnection capacity is limited, which reduces cross-border exchanges opportunity, especially during scarcity periods. In this section, we assume a fixed transmission capacity T between A and B. We focus on extending our main proposition (3 : incompatibility between Curtailment Sharing and Costs local).

8.3.1 Changes in the model set-up

Electricity generation In the following, we assume, without loss of generality, that $k_A \geq k_B$.

Energy market In the following, we assume a fixed interconnection capacity T. We set it voluntarily low enough to be binding. When $l \leq k_B$, both countries have enough domestic capacity to meet their demand, so the interconnector is not binding. When the regional capacity is above the regional demand ($k_B < l < \frac{k_A+k_B}{2}$), zone A exports its available generation capacity margin to zone B. The maximum amount zone A can export before the zone reaches scarcity is $\frac{k_A-k_B}{2}$ (exports observed at the limit $2l = k_A + k_B$). When $\frac{k_A+k_B}{2} < l$, there is curtailment. Assuming curtailment sharing, exports from A to B are $\frac{k_A-k_B}{2}$. So, across all demand scenarios, exports from A to B never exceed $\frac{k_A-k_B}{2}$. Therefore the transmission capacity T is binding only if $T < \frac{k_A-k_B}{2}$. In the following, we therefore assume $T < \frac{k_A-k_B}{2}$.

Capacity market Because the interconnection capacity is binding, zone B experiences scarcity periods (prices reaching P_C) more often than zone A (as soon as $l > k_B + T$). Therefore, generators scarcity revenues, and the expression of capacity payments, differs in the two countries. The capacity price in zone B is defined by the perfect competition assumption: $(1-F(k_B+T))(P_C-C)-r+m_B =$

0. Hence we obtain:

$$m_B = (VOLL - C)(1 - F(K^*)) - (P_C - C)(1 - F(k_B + T))$$

8.3.2 Changes in the welfare components

National welfare - Energy market component - Curtailment-Sharing

Assuming curtailment sharing, the energy market welfare component for country B is the following.

$$W_B^{ES}(k_A, k_B) = \int_0^{k_B+T} (VOLL - C)lf(l)\,dl + \int_{k_B+T}^{\infty} (VOLL - P_c)(k_B + T)f(l)\,dl$$

The load is fully served in country B, until the interconnector reaches its limit ($l \leq k_B + T$) (first integral). When $l > k_B + T$, zone A systematically exports T towards zone B to tend towards curtailment sharing, even though the curtailment ratios can no longer be equalized as the interconnector is binding (second integral). Indeed, noting s_A, s_B the served load in respectively, zone A and B, we have $s_B = k_B - T$ and $s_A = k_B + T$, so $s_B - s_A = k_B - k_A + 2T < 0$ (because $T < \frac{k_A - k_B}{2}$).

Using the properties (1) (2) of the normal demand distribution function we obtain:

$$W_B^{ES}(k_A, k_B) = (VOLL - C)[\mu F(k_B + T) - \sigma^2 f(k_B + T)] + (VOLL - P_C)(k_B + T)[1 - F(k_B + T)]$$

$$\frac{\partial W_B^{ES}}{\partial k_B}(k_A, k_B) = (P_C - C)(k_B + T)f(k_B + T) + (VOLL - P_C)(1 - F(K_B + T))$$

National welfare - Energy market component - Costs-Local

When capacity costs are allocated locally, country B pays only for the cost of domestic capacity (k_B): $W_B^{CL}(k_A, k_B) = -k_B m_B(k_A, k_B)$.

Considering the expression of capacity costs described above, we obtain the following derivative component:

$$(\frac{\partial W_B^{CL}}{\partial k_B})(k_A, k_B) = -(P_c - C)k_B f(k_B + T) - (VOLL - C)(1 - F(K^*)) + (P_C - C)(1 - F(k_B + T))$$

8.3.3 Results

Curtailment Sharing and Costs Local (extension of Section 3.2)

Proposition When interconnection capacity is limited, a capacity distribution k_A, k_B cannot be stable if the interconnector is binding ($T >\mid \frac{k_A - k_B}{2} \mid$). Therefore, proposition 3 can be generalized to when interconnectivity is limited.

Proof Combining the derivative components, we obtain

$$\frac{\partial W_B}{\partial k_B} = (P_C - C)(f(k_B + T))T + (VOLL - C)(F(K^*) - F(k_B + T)))$$

If $k_B+T \leq K^*$ then we obtain directly $\frac{\partial W_B}{\partial k_B} > 0$. So country B has an incentive ton increase domestic capacity to reduce curtailment. If $k_B + T > K^*$, then we are out of the optimal conditions. Indeed, at optimal we should have $K^* = \frac{k_A+k_B}{2}$, hence, $k_B + T > \frac{k_A+k_B}{2}$, implying $T > \frac{k_A-k_B}{2}$ which contradicts our initial assumption on the binding interconnection capacity.

So, as long as the interconnector is binding $k_B < k_A + 2T$, the optimal capacity level is not a sable Nash equilibrium. Country B has an incentive to increase the domestic capacity, until the interconnector is never binding, and we fall back into the case described in section 3.2.

8.4 What if capacity costs are shared, but not curtailment?

In our core model, we did not consider the case in which capacity costs would be shared (Costs-Sharing), but not curtailment (Curtailment-Reservation, or Curtailment-Local). The reason is, such a scenario appears highly unlikely. In this Appendix, we explore such configurations. We show that they could result in overprocurement of capacity. This enables us to fill Table 2.

8.4.1 Results

Curtailment-Local or Curtailment-Reservation and Costs-Sharing

Proposition Combining Cost-Sharing and Curtailment-Local, the optimal regional capacity ($2K^*$) is not a stable Nash equilibrium in the non-cooperative scenario.

Proof We combine the welfare derivative components (16)+(8) or (16)+(9. At the symmetrical cooperative equilibrium point (k_A, k_B)=(K^*, K^*), we obtain:

$$\frac{\partial W_A}{\partial k_A} = \frac{1}{2}(VOLL - P_c)(1 - F(K^*)) > 0$$

Proposition Combining Cost-Sharing and Curtailment-Reservation, the optimal regional capacity ($2K^*$) is not a stable Nash equilibrium in the non-cooperative scenario.

Proof We combine the welfare derivative components (17)+(10) or (17)+(11.. At the symmetrical cooperative equilibrium point (d_A, d_B)=(K^*, K^*), we obtain:

$$\frac{\partial W_A}{\partial d_A} = \frac{1}{2}(VOLL - P_c)(1 - F(K^*)) > 0$$

Analysis When the energy available during scarcity is allocated based on local or procured capacity, while capacity costs are shared, it is not possible to achieve the optimal regional capacity level ($2K^*$). The symmetrical optimal capacity distribution (K^*, K^*) is not a stable equilibrium. Country A can increase its consumers' welfare by increasing its domestic or procured capacity (k_A, ord_A). The explanation is as follows. If country A procures additional capacity, it will save on curtailment costs, because curtailment is allocated based on local or procured capacity. It will also increase capacity costs, but not that much, because those costs are shared with the neighboring country. In turn, the marginal curtailment cost savings from increasing capacity demand are higher than the additional capacity costs. An preference for "reserved" capacity appears. As a result, we can expect over-procurement of capacity. We emphasize that such a scenario, in which the capacity costs would be shared but not the benefits, is highly unlikely.

Proposition The symmetrical national equilibrium capacity in the non-cooperative scenarios is the following: $K_{eq} = F^{-1}(1 - \frac{r}{2VOLL - P_c - C}) > K^*$

Proof Using the welfare components described in 2.3, we compute the equilibrium local capacity or capacity demand (noted k_{eq}), which verifies the non-cooperative equilibrium condition for both countries : $\frac{\partial W_A}{\partial k_A}(k_{eq}, k_{eq}) = 0$ or $\frac{\partial W_A}{\partial d_A}(k_{eq}, k_{eq}) = 0$. We use the properties of the normal distribution function, in particular F admits an inverse function.

Analysis When the capacity costs are shared equally between the two countries, while curtailment is allocated based on local or reserved capacity, we can expect over-procurement of capacity ($K_{eq} < K^*$). This is not surprising, because at the optimal capacity point (K^*, K^*), both countries can individually increase their national welfare by increasing the capacity they procure.

Numerical illustration For numerical illustration, we compute the relative deviation from the optimal equilibrium capacity ($(K_{eq} - K^*)/K^*$) using the values described in section 2.2. We additionally compute the resulting deviations in loss of load expectation, in capacity costs, and in consumers welfare at regional level (using the expressions from section 2).

Cost allocation Curtailment allocation	Sharing Local/Reservation
Relative capacity deviation	+1.7%
Relative LOLE deviation	−41%
Relative ENS deviation	−44%
Relative capacity costs deviation	+17%
Absolute energy market surplus deviation	+2071 M€/year
Absolute capacity costs (savings) deviation	−2130 M€/year
Absolute welfare deviation	−59 M€/year

If capacity costs are shared, and curtailment is allocated based on domestic or procured capacity, we obtain an over-procurement of around +1.7%. Though this relative change appears quite low, it reduces the loss of load expectation by 41%, and energy not served by 44%
. As scarcity revenues decrease, the capacity costs conversely increase, by around +17%. At regional level, the resulting absolute welfare loss reaches −59 M€/year.

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