Cross-border effects of capacity remuneration schemes in interconnected markets: who is free-riding?

Working paper. comments welcome.

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Abstract

We study the welfare impacts of national support schemes for generation capacity when energy markets are interconnected. Assuming perfect competition and inelastic demand, we compare the cases of an energy-only market with no support scheme, with a market with capacity payment and a market with strategic reserve. We find that if transmission system operators (TSOs) can't control exports and neighbours stick to an energy-only paradigm, a capacity payment is ineffective unless transmission capacity is small. If TSOs can control exports, the capacity payment attracts investments and foreigner's security of supply shrink. A neighbouring energy-only or strategic reserve market will thus be prejudiced in the long-run and may have to implement a capacity payment as well in order to meet its security of supply standard. Hence, capacity payments may spread in Europe thanks to their negative cross-border effect on investment incentives. This is in sharp contrast with the conventional wisdom, based on short-term arguments, that energy-only market will free-ride the security of supply provided by neighbouring capacity markets. A strategic reserve has no negative cross-border welfare externalities, but may allow neighbours to free-ride capacity. Our conclusions urge for the harmonization of capacity remuneration schemes across Europe.

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1 Introduction

Since the liberalization process began in the early 90s, the European power sector has been increasingly exposed to market-based mechanisms, as opposed to national planning. Investments are increasingly market-driven, with prices supposed to give life to a socially optimal capacity mix and adequacy level. However, the power market is still exposed to many constraints. The upstream market has so far remained very concentrated and demand remains largely inelastic, requiring the implementation of numerous regulatory firewalls such as price caps, in a move to tame market power abuse. Many regulators have recently observed that the price signal alone no longer generated an "adequate" level of capacity according to their Security of Supply (SoS) standards, a trend that was accentuated by fast renewables development. Thus, many European regulators are considering the implementation of some form of capacity remuneration mechanisms (CRMs) to directly remunerate investment (and not only energy), leading to a patchwork of assorted and complex market designs– see appendix A for a summary of current and forthcoming schemes in Europe. These regulatory interventions have so far been designed in a solipsistic manner, as regulators have been taken by surprise by the unintended effects of renewables penetration and try to find a quick-fix to support capacity. This regulatory recourse is already very complex and controversial when only one market is considered, so much so that all CRMs ignore cross-border effects or at best take account of imports in an implicit manner. This headlong rush might prove very costly in the long run. This paper proves that cross-border effects do exists, and they might be far from negligible. On top of that, the victim might not be the one who first crosses our mind: we show that the problem in the long-run does not lie so much in capacity free-riding (at the *expense* of the market with capacity support), but rather in unfair investment competition (at the *benefit* of the market with capacity support).

We'll compare the benchmark case of an energy-only market without a support scheme (market "EO"), with a market providing a capacity payment (market "CP") and with an energy-only market endowed with a strategic reserve (market "SR").

We find several results. First, by construction of our model, when markets are not connected, the energy-only market is the cheapest paradigm. If capacity is deemed too low, implementing a strategic reserve or a capacity payment are equivalent in terms the welfare costs to reach a given SoS level: even though the direct, upfront cost of capacity support is greater when the security of supply standards are met with capacity payments CP, compared with a strategic reserve SR, the energy prices are (weakly) higher in the strategic reserve paradigm. Hence, the higher upfront cost of implementing support through a capacity payment (relative to a strategic reserve) is offset indirectly, through smaller electricity bills.

Second, when markets EO and CP are connected, CP will export to EO, possibly at high prices: capacity in CP gets more profitable and capacity payment can be scaled down. Conversely, investing in EO is less profitable due to CP's large (supported) operational capacity and less capacity will be built there. Market CP is better off post market integration. EO is indifferent in terms of welfare, even though its SoS may be degraded if transmission system operators (TSOs) are allowed to control exports. If EO's SoS reaches unacceptably low levels, the energy-only market might be forced to implement a CRM as well. If TSOs are not allowed to control exports, the CRM merely displaces capacity, but has no effect on security of supply. In that case, a market willing to increase its SoS through a capacity payment will have an incentive to decrease its interconnection capacity with neighbours.

Third, interconnecting a market CP with capacity payment with a strategic reserve market is similar to interconnecting a capacity payment with an energy-only market EO: CP's support scheme is alleviated by additional revenues when it exports at high prices to SR. If TSOs control can control exports, SR has to build up strategic reserve by an amount equivalent to the increment of capacity in CP following the implementation of the capacity payment to maintain its SoS level.

Table 5 summarizes the cross-border effects of CRMs, when there are no explicit corrective transfers from one scheme to the other, price cap is set at a (common) Value of Lost Load (VoLL), TSOs are allowed to control exports, and each market sticks to its capacity support paradigm before and after interconnection:

Local scheme	*Enjoys positive externality from*	*Endures negative externality from*
EO	SR**	CP*
SR	EO	CP
CP	SR $\sim$ EO	-

Table 1: Gains from interconnecting with neighbours
*EO is welfare-neutral, but gets degraded SoS
** EO is welfare-neutral, but gets improved SoS

2 Litterature review

The internal energy market, advocating coordination between member states and energy market coupling, is a pivotal instrument to meet the European commission's target in terms of affordability, security, sustainability of power supply (see [European commission, 2010]). National markets are requested to better integrate with neighbours, in order to gain efficiency through increased competition and diversification effects ([Creti and Fumagalli, 2010], [Jamasb and Pollitt, 2005]). However, concerns over the conflicts between national market designs and the internal energy market haven't eased. The need for an assessment of cross-border effects of capacity remuneration schemes has been repeatedly stressed by many regulators ([ACER, 2013], [CEER, 2013], [RAP, 2013]), actors of the energy markets (TSOs and utilites) institutions ([IEA, 2014]). Quite surprisingly, relatively little has been made yet on the research side. Many discussions focus on the short-term (usually positive) cross-border effects of CRMs, while by nature discussions on investment incentives should rather focus on the long-run effects, which we'll show can be negative. A hint of our results can be found in the empirical literature, showing that cross-border trade when market designs differ may be inefficient([McInerney and Bunn, 2013], [Viljainen et al., 2013]). Only few natural experiments of interconnected markets with different designs are currently available, even though this phenomenon will likely expand very fast in Europe in the next decade.

One notable and inspiring effort to address long-run cross-border inefficiencies by [Gore and Meyer, 2015] studies the interaction between an energy-only market and a market with a strategic reserve, and between an energy-only market and market with reliability options. They find that unilateral implementation of a capacity mechanism may have negative welfare effects in the neighbouring market, which may force it to change its own market design. These results, even though it relies on numerical simulations on stylized markets, are fully consistent with ours. [Thema, 2013], in a report to the EU commission conclude that individual capacity mechanisms can distort the allocation of investment, with investment likely to shift from countries with no CRM to countries with a CRM. [Sweco, 2014], in a multi-client report finds that total consumer costs are typically higher in countries with a CRM, and reduced in Energy-only market. They highlight that a CRM can reduce the SoS in the neighbouring market, thereby leading it to consider implementing a CRM as well. Those reports rely on numerical simulations and qualitative descriptions, and lack a formal proof.

Several market designs have been proposed so far, but none provides a fully satisfying solution to mitigate undesired cross-border effects. [Eurelectric, 2015] pleads for cross-border participation of

CRM. Market coupling should be preserved. Transmission operators should be given an additional congestion rent based on cross border capacity allocation. It should not be possible to participate with the same capacity in more than one CRM at a time. [Frontier Econonomics, 2015] recommends that interconnected generators bid directly in the CRM auction and receive the capacity payments. They would then face a penalty for their own or the interconnectors non-delivery of power during a stress event. [Mastropietro et al., 2014] and [Mastropietro et al., 2015] suggest a conditional nomination rule for transmission capacity, to be activated when scarcity is declared on both sides of the interconnection. None of these propositions fixes the phenomenon we will highlight in this paper.

3 Model and Benchmark

3.1 The model

The basic elements of this model are very similar to [Creti and Fabra, 2007]. There are three markets j denoted EO, CP and SR, with local inelastic demand l_{eo}, l_{cp} and l_{sr} respectively, distributed according to $F_j(l)$ on $[0, \infty]$. All markets use the same, unique, technology with capacity costs r and marginal costs c. EO is energy-only, while market CP meets a SoS target through a capacity payment, while market SR has a strategic reserve, producing only when the local market is tight (i.e. when price hits the price cap). In this paper, we'll successively connect those countries two by two with a bidirectional transmission capacity T. T is exogenous, does not induce losses[1]. Transmission may be congested in some states of the world, or never congested. We are looking for equilibrium capacities, and the impact on consumers' overall electricity bill in each market. Throughout the paper, we'll assume that there is free-entry in the generation sector.

Note that when loads l_m are identically distributed and markets are isolated, a given SoS standard translates monotonically in a given capacity target. The more stringent the standard, the higher the target. If they have the same SoS target, two isolated market both want to implement a total capacity level k^T, where exponent T denotes the target capacity.

There is a price cap on the energy market, set at the Value of Lost Load of consumers. Perfect competition implies that price p is at marginal cost c, where and when demand is below available operational capacity, and is at $\bar{P}$ otherwise. Consumer surplus per unit of energy consumed is $VoLL - p = \bar{P} - p$. Throughout this paper, we assume that $0 < r < \bar{P} - c$, meaning that a strictly positive quantity of capacity will be installed in any market, even absent a capacity remuneration scheme.

[1] the no-losses assumption will be relaxed in appendix G

All agents are risk-neutral. Note that in our model, Security of Supply as such does not yield any welfare benefit. It is just a target that has to be met: largely exceeding the target does not yield any additional satisfaction to the TSOs or consumers, compared to a situation where the target is just met – set aside the usual welfare increase due to additional demand coverage. We'll use "Expected Energy Non Served" (EENS) as a Security of Supply concept, denoted $\mathcal{L}$: the smaller $\mathcal{L}$, the higher the SoS. The energy-only market gives rise to an equilibrium capacity k^*, which gives a level security of security of supply $\mathcal{L}^*$. If the policy-maker finds that $\mathcal{L}^*$ is low enough, the market will stay energy-only. Otherwise he will have to support capacity, either in the form of a capacity payment or a strategic reserve.

3.2 Benchmark: Isolated markets

To make market designs easily comparable in this section, assume that demands in each market are i.i.d, such that EO, CP, and SR are identical –set aside the market design. Superscript i stands for "isolated", and will be used to identity benchmark values when a market isn't connected to any other market.

3.2.1 Market EO: Energy only

A market stays Energy Only if and only if the market is able to provide –without support– the required level of security of supply or more, that is: $\mathcal{L}^T < \mathcal{L}^*$, where T denotes the target EENS. No arbitrage means price is c as long as demand is less than capacity, $\bar{P}$ otherwise.

Operational capacity assuming free entry is such that investors just break even. Their profit is:

$$\pi^i_{eo} = 0 = (\bar{P} - c)(1 - F(k^*)) - r \Rightarrow k^* = F^{-1}(1 - \frac{r}{\bar{P} - c})$$

This translate into a SoS level[2] : $\mathcal{L} = \mathcal{L}^* = \int_k^\infty (l - k^*) f(l) dl$

The welfare in EO is:

$$W^i_{eo} = W^* = (\bar{P} - c)\left(\int_0^{k^*} l f(l) dl + (1 - F(k^*))k^*\right) - rk^* \tag{1}$$
$$= (\bar{P} - c)\left(\int_0^{k^*} l f(l) dl\right) \tag{2}$$

The free-entry condition in the supply sector ensures that all welfare is captured by consumers.

[2] $\gamma = \frac{r}{\bar{P}-c}$ is the probability that a scarcity appears, but give no information on its magnitude. In this paper, with thus prefer to use the EENS $\mathcal{L}$ as a SoS criteria

3.2.2 Market CP: Capacity payment

Assume that an identical market CP wants to achieve a greater level of SoS: it seeks to set $k_{cp} = k^T$. To enforce it, it needs to support investment with a subsidy m per capacity unit. This award m^i can be a direct capacity payment, or the outcome of a centralized or decentralized auction. Free entry in market CP means:

$$\pi^i_{cp} = 0 = m^i + (\bar{P} - c)(1 - F(k^T)) - r$$

Welfare in CP is:

$$\begin{aligned}
W^i_{cp} &= (\bar{P} - c)\left(\int_0^{k^T} lf(l)dl + k^T(1 - F(k^T))\right) - rk^T && (3)\\
&= (\bar{P} - c)\left(\int_0^{k^T} lf(l)dl\right) - m^i k^T && (4)\\
&= W^* + (\bar{P} - c)\left(\int_{k^*}^{k^T} lf(l)dl\right) - (\bar{P} - c)\left(F(k^T) - F(k^*)\right)k^T && (5)\\
&= W^* - \underbrace{(\bar{P} - c)\left(\int_{k^*}^{k^T} (k^T - l)f(l)dl\right)}_{wefare\ cost\ of\ SoS} && (6)
\end{aligned}$$

Unsurprisingly, in our setting where SoS is not valued as such, but just represents an additional constraint in TSOs welfare-maximization problem, implementing some form of capacity support leads to a decrease in welfare: capacity is no longer built on a market basis only, and some spare capacity needs to be financed[3]. Of course, the flip side of the coin is greater SoS, as the probability that curtailment occurs is $(1-F(k^T))$ instead of $(1-F(k^*))$ in the Energy-only market. Similarly, expected curtailed demand is $\mathcal{L}^T = \mathcal{L}^i(k^T) = \int_{k^T}^1 (l - k^T)f(l)dl < \mathcal{L}^* \int_{k^*}^1 (l - k^*)f(l)dl$.

3.2.3 Market SR: Strategic Reserve

The price signal is the same as in market EO, as SR's strategic reserve is activated if and only if price (weakly) exceeds the price cap.

The price is c if $l \leq k_{sr}$. If $l > k_{sr}$, the strategic reserve is activated and price is $\bar{P}$. There is curtailment if and only if $l > k^T$.

The free-entry condition is the same as in the Energy-only case, as the strategic reserve does not

[3]A more detailed analysis of the costs of SoS can be found in appendix F

modify prices:

$$\pi^i_{sr} = 0 = (\bar{P} - c)(1 - F(k^i_{sr})) - r \Rightarrow k^i_{sr} = k^* = F^{-1}(1 - \frac{r}{\bar{P} - c})$$

The TSO needs to provide $k^{SR} = k^T - k^*$ strategic reserves to meet its target. As in the Belgian case, we assume that the TSO is just reimbursing the marginal cost to producers, when they are active. Therefore the TSO gets $\bar{P} - c$ from each energy unit produced by the SR[4]. This income, will allow to soften the burden of capacity support. The total expected costs of the SR is thus:

$$\begin{aligned}
Cost^i_{sr} =& r(k^T - k^*) - (\bar{P} - c)\left(\int_{k^*}^{k^T} (l - k^*)f(l)dl + (1 - F(k^T))(k^T - k^*)\right) && (7)\\
=& (\bar{P} - c)(1 - F(k^*))(k^T - k^*) - (\bar{P} - c)\left(\int_{k^*}^{k^T} (l - k^*)f(l)dl + (1 - F(k^T))(k^T - k^*)\right) && (8)\\
=& (\bar{P} - c)\left(\int_{k^*}^{k^T} (l - k^*)f(l)dl - (F(k^T) - F(k^*))(k^T - k^*)\right) && (9)\\
=& (\bar{P} - c)\left(\int_{k^*}^{k^T} (k^T - l)f(l)dl\right) && (10)
\end{aligned}$$

The total welfare is therefore:

$$\begin{aligned}
W^i_{sr} =& (\bar{P} - c)\int_0^{k^*} l_{sr}f(l)dl + (\bar{P} - \bar{P})\int_{k^*}^{k^T} lf(l)dl + (\bar{P} - \bar{P})(1 - F(k^T))k^T && (11)\\
&- (\bar{P} - c)\left(\int_{k^*}^{k^T} (k^T - l)f(l)dl\right) && (12)\\
&= W^* - (\bar{P} - c)\left(\int_{k^*}^{k^T} (k^T - l)f(l)dl\right) && (13)\\
&= W^i_{cp} && (14)
\end{aligned}$$

Thus, in our setting with free-entry and risk-neutrality the total social cost is the same with both support schemes. Given that consumers enjoy the same service in both markets (demand served until k^T, curtailed afterwards), and pay the same total price we must have that $W^i_{sr} = W^i_{cp}$. In the strategic reserve paradigm, frequent high prices on the energy market means the upfront costs of reserve capacity decrease. In the capacity payments paradigm, upfront costs are higher as high wholesale prices are

[4] One can assume higher payment to active SR plants, up to $\bar{P}$. This would not change the total costs of the SR, as the TSO would have to pay a lesser share of the fixed costs, which in turns benefits consumers. We assume here that the least risk averse agent (i.e. the TSO) gets the uncertain revenues and pays c to producers for each generated unit of electricity

rare, and therefore investors need to be largely incentivized. The consumers recover this high cost through lower energy prices.

The intuition for this is that given there is free entry and both markets want to achieve the same level of capacity, consumers pay the exact cost of producing electricity, given (an exogenously fixed) total capacity –and nothing more. That is, they need to pay for capacity fixed costs, plus marginal costs of production [5]. The price cap does not appear here as it is simply a transfer from consumers to producers, and those realize no profit anyway.

The rest of the paper focuses on the EO/CP interaction. SR/CP and SR/EO cases are treated in appendix B, C, D and E .

4 Sharing rules in case of concomitant scarcity

When two markets are interconnected, it is crucial to define precisely what happens when both markets endure scarcity. In a first paradigm, consistent with most network codes (see [Mastropietro et al., 2014]), TSOs will ensure stability on their own network and avoid curtailing their consumers. Thus, they may curtail export in order to meet local demand. In a second paradigm, more consistent with the security of supply directive (2005) [6] and the spirit of the Internal Energy Market, TSOs would coordinate, so that the magnitude of the curtailment is the same on both sides of the border. This paradigm implies solidarity between markets. Of course, there might be other allocation rules (energy allocated pro-rata of capacity, pro-rata of local demand...), but we believe those two paradigms correspond to two extreme situations and adding intermediary allocation rules would add little insight.

As will be shown in section 8.1, the second paradigm leads to an irrelevance result for unilaterally implemented capacity markets. With non-binding transmission capacity, a CRM based on a capacity payment only displaces capacity from one market to the other. Thus, there is no creation of capacity. If markets ex-ante agree and commit to arrange cross-border flows so that both markets are equally curtailed, then the location of the capacity does not matter, as energy will be dispatched according to where demand is, and not where supply is. For this reason, in this paradigm, there is no point implementing a CRM. It is therefore likely that regulators currently implementing a CRM will try to manage their exports such that the CRM does improve their markets' SoS. Thus, in the following we investigate a rather extreme case where TSOs have domestic preference and can curtail exports in case the coverage of their domestic demand is endangered. Milder sharing rules might emerge in

[5] it is important to note that we assumed risk neutrality. If agents are risk-averse, those conclusions may not hold

[6] Security of Supply Directive (2005/89/EC), states that Member States shall not discriminate between cross-border contracts and national contracts.

practice, but we believe the main insights carry over.

5 Interconnected EO/CP markets – symmetric markets

Let us now take an energy only market EO, interconnected with a market with capacity payment CP. CP's firms will sell in market EO, potentially at high prices: interconnection benefits CP's firms, and in turn CP's consumers. Figure 1 illustrates the phenomenon we are going to highlight in this section: In the short run, EO's consumers are better off, as CP can export to EO when EO's capacity is insufficient. However, CP's exports depress EO prices and forces exit from EO. Total welfare is increased compared to the isolated case thanks to a better use of available total capacity. All this increase is captured by CP. In the long run, EO's welfare is unaffected, but its security of supply level shrinks (see figure 1). If its SoS becomes unacceptably low, EO will implement a CRM as well.

We first assume that a TSO can (1) control exports in case of system stress [7], but (2) does not control imports[8], some assumptions reflecting current national regulations. Adding some small cross-border transaction costs or transmission losses will then allow to relax the first assumption. We'll show that curtailing imports in times of scarcity yields a negative benefit to both parties and assumption (2) is therefore likely to hold in reality.

[7]all national network codes allow TSO to curtail exports to ensure that demand is satisfied in their system
[8]The SoS directive explicitly stresses that TSOs shall not discriminate between national and foreign generation

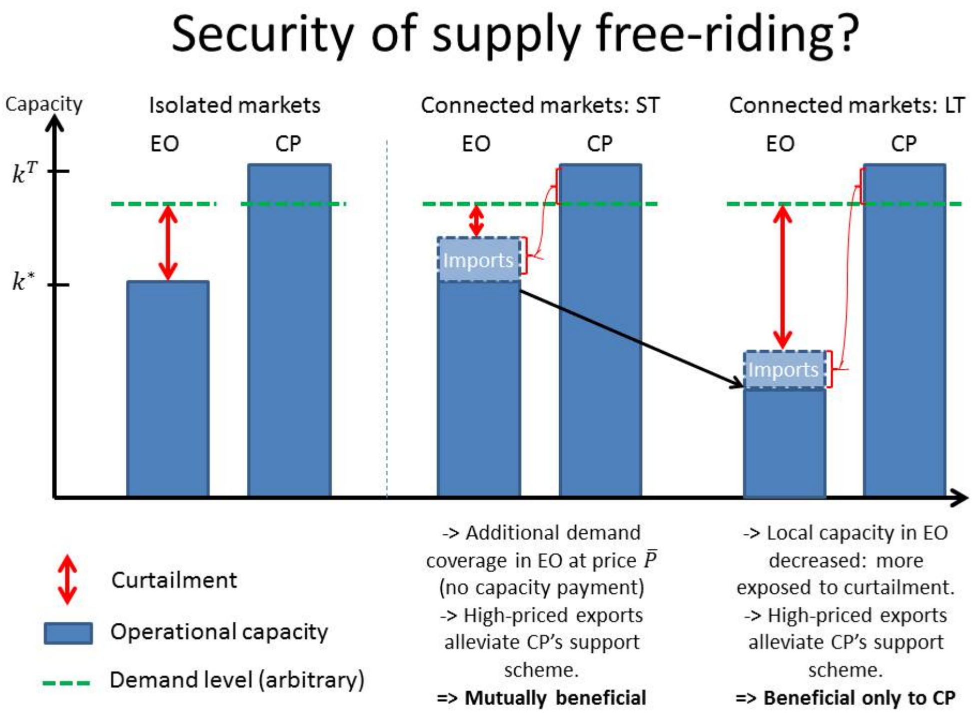


Figure 1: EO free-rides CP's capacity in the short term, but in the long run its local capacity decreases, together with its SoS level

In this section, we assume that demands in EO and CP are perfectly correlated. That is, in all states of the world $l_{eo} = l_{cp} = l$. This assumption will be relaxed in the next section.

5.1 Transmission is never binding

Transmission is never binding if and only if $T > \frac{k^T - k_{eo}}{2} = k^T - k^*$. As in the isolated case, price is at marginal cost c as long as as total demand is less than total capacity. When demand exceeds capacity, price jumps at $\bar{P}$. Indeed, as soon as there is some curtailment in one of the two markets, prices hit the cap: if price were lower in the loose market, a generator would want to sell in the tight market instead of the loose one.

The possible states of Nature can be summarized as follows:

Demand	p_{eo}	p_{cp}	Exports CP $\rightarrow$ EO	Profits made by CP in EO
$l \leq k_{eo}$	c	c	0	0
$k_{eo} < l \leq \frac{k^T+k_{eo}}{2}$	c	c	$l - k_{eo}$	0
$\frac{k^T+k_{eo}}{2} < l \leq k^T$	$\bar{P}$	$\bar{P}$	$k^T - l$	$(\bar{P}-c)(k^T-l)$
$k^T < l$	$\bar{P}$	$\bar{P}$	0	0

Table 2: States of Nature – correlated demand: $l_{eo} = l_{cp} = l$, transmission is not binding. No arbitrage imposes that price is at marginal cost as long as there is spare capacity ($2l < k^T + k_{eo}$), and hits $\bar{P}$ otherwise.

Demand coverage in CP is unaffected by EO's capacity level, as CP's consumers gets priority over CP's capacity in case of scarcity, and EO's capacity is less than CP's. Therefore with correlated loads if CP is tight, *a fortiori* EO is tight and can't export. Thus, $k_{cp} = k^T$.

Free-entry conditions are:

$$Market\ CP: \quad r = m + (\bar{P}-c)\left(1 - F\left(\frac{k^T + k_{eo}}{2}\right)\right) \tag{15}$$

$$Market\ EO: \quad r = (\bar{P}-c)\left(1 - F\left(\frac{k^T + k_{eo}}{2}\right)\right) \tag{16}$$

Comparing 15 and 16 shows that $m = 0$: as long as there is a strictly positive amount of capacity in market EO, CP will have to pay a negligible upfront payment m to attract investments.

We have that $\frac{k^T+k_{eo}}{2} = F^{-1}(1 - \frac{r}{\bar{P}-c}) = k^* \Rightarrow k_{eo} + k^T = 2k^*$, meaning total capacity stays at the optimal level, whatever CP's capacity target is (provided that capacity in EO remains strictly positive).

Welfare in the market with a capacity payment

Welfare in market CP, given that $k_{cp} = k^T$ and $k_{eo} = 2k^* - k^T$ is:

$$\begin{aligned} W_{cp}(k^T, 2k^* - k^T) =& (\bar{P}-c)\int_0^{k^*} lf(l)dl + (\bar{P}-\bar{P})\int_{k^*}^{k^T} lf(l)dl + (\bar{P}-\bar{P})\left(1-F(k^T)\right)k^T - m * k^T \\ =& (\bar{P}-c)\left(\int_0^{k^*} lf(l)dl\right) \qquad (17) \\ =& W^* \qquad (18) \end{aligned}$$

CP consumers enjoy decreased costs compared to the isolated case. Interestingly the cost reduction

(= welfare increment, since demand coverage is unchanged compared with the isolated case), is exactly the cost of the support scheme when markets are isolated (either with SR or CP). Thanks to the interconnection with its energy-only neighbour, CP meets its SoS target at zero cost!

Welfare in the energy-only market

In terms of welfare, market EO is indifferent between curtailing consumers and getting high-priced imports. One can assume that CP exports at a price just below $\bar{P}$ so that EO does import from CP (and is just indifferent between importing and curtailing). Note that we have that $k_{cp} + k_{eo} = 2k^*$: capacity in EO decreases such that total capacity remains equal to optimal capacity (according to EO's market-based standards).

$$\begin{aligned} W_{eo} =&(\bar{P} - c)\left(\int_0^{k^*} l_{eo} f(l_{eo}) dl_{eo}\right) + (\bar{P} - \bar{P})\left(\int_{k^*}^{k^T} (2k^* - l_{cp}) f(l_{eo}) dl_{eo} + (1 - F(k^T))(2k^* - k^T)\right) \\ =&W^* \end{aligned} \tag{19}$$

When transmission is non-binding, the following proposition holds:

Proposition 1 *With perfectly correlated demands, a market with a capacity payment funds its capacity remuneration scheme through exports, at the expense of its energy only neighbour's security of supply. Overall security of supply remains unchanged as long as capacity in the energy-only market remains strictly positive. Overall welfare costs of SoS are smaller than in the isolated case, thanks to increased utilization of CP's capacity.*

Proof. As proven above, EO is indifferent to CP's decision to implement a capacity payment, from a welfare point of view. *A fortiori* EO is also indifferent to k^T. However, its SoS is reduced. The expected curtailment was $\mathcal{L}^* = \int_{k^*}^1 (l_{eo} - k^*) f(l_{eo}) dl_{eo}$. After interconnection it becomes:

$$\mathcal{L}_{eo}^{connected} = \int_{k^*}^{k^T} (2l - 2k^*) f(l) dl + \int_{k^T}^{\infty} (l - k) f(l) dl \tag{20}$$

$$= \mathcal{L}^* + \int_{k^*}^{k^T} (l - k^*) f(l) dl + (1 - F(k^T))(k^T - k^*) > \mathcal{L}^* \tag{21}$$

■

Note that in a rather extreme case, if k^T is so large that k_{eo} falls to 0 (i.e. target capacity in CP is twice the equilibrium level); market EO is used as a buffer to market CP's excess capacity, and has a very low SoS level. However, if $k^T \gg 2k^*$, it may be the case that the energy-only market is better off when it is connected with CP than when it isn't: if capacity in CP is so large that EO's SoS target is met even with zero local capacity, then EO's welfare is improved. Only in those extreme cases one can say that EO "free-rides" CP's capacity in the long run. This case will be investigated further in the next section.

5.2 Transmission is binding

When transmission is binding (i.e. $T \geq k^T - k^*$), the possible states of Nature can be summarized as follows:

Demand	p_{eo}	p_{cp}	Exports CP $\rightarrow$ EO	Profits made by CP in EO	Congestion rent
$l \leq k_{eo}$	c	c	0	0	0
$k_{eo} < l \leq k_{eo} + T$	c	c	$l - k_{eo}$	0	0
$k_{eo} + T < l \leq k^T - T$	$\bar{P}$	c	T	0	$(\bar{P} - c)T$
$k^T - T < l \leq k^T$	$\bar{P}$	$\bar{P}$	$k^T - l$	$(\bar{P} - c)(k^T - l)$	0
$k^T < l$	$\bar{P}$	$\bar{P}$	0	0	0

Table 3: States of Nature – correlated demand: $l_{eo} = l_{cp} = l$, transmission is binding

Assume CP's TSO owns a share $\alpha \in [0, 1]$ of the transmission rights. Each market allows entry: the zero-profit condition pins down the installed capacities:

$$\pi_{eo} = 0 = (\bar{P} - c)[1 - F(k_{eo}^c + T)] - r \Rightarrow k_{eo}^c = F^{-1}(1 - \frac{r}{\bar{P} - c}) - T = k^* - T \tag{22}$$

Where subscript c denotes the "congested" case. Note that $k_{eo}^c = F^{-1}(1 - \frac{r}{\bar{P}-c}) - T = k_{eo}^i - T > k_{eo}^i - \frac{k^T - k_{eo}}{2} = k^* - k^T + \frac{k^T + k_{eo}}{2} > 2k_{eo}^i - k^T$. Hence $k_{eo} < k_{eo}^c < k_{eo}^i$.

Again, demand coverage in CP is unaffected by the connection with EO, as CP's consumers gets priority over CP's generation in case of scarcity, and EO's capacity is less than CP's.

Costs to CP consumers are alleviated by potential high-priced exports to EO. Unlike in the uncongested case, capacity in CP is no longer a perfect substitute to capacity in EO. Therefore, denoting by subscript c the congested case, there will indeed be a strictly positive capacity payment m^c. Free-entry in market CP yields:

$$r = m^c + (\bar{P} - c)\left(1 - F\left(k^T - T\right)\right) \tag{23}$$

$$\Rightarrow 0 < m^c = (\bar{P} - c)\left(F\left(k^T - T\right) - F\left(k^*\right)\right) \leq (\bar{P} - c)\left(F\left(k^T\right) - F\left(k^*\right)\right) = m^i \tag{24}$$

Note that the capacity payment is now positive (unlike in the no-congestion case), but less than the payment in isolation.

CP's gross consumer surplus is unchanged. Thus, the cost reduction translates in an equivalent increase in welfare. Similar calculations as before yield:

$$W_{cp} = W^i_{sr,cp} + (\bar{P} - c)\left(\alpha \overbrace{T(F(k^T - T) - F(k^i_{eo}))}^{\text{congestion rent}} + \overbrace{\int_{k^T - T}^{k^T} (k^T - l_{eo}) f(l_{eo}) dl_{eo}}^{\substack{\text{export idle capacity to } CP \to EO \\ \text{absent congestion}}}\right) \tag{25}$$

Again, in terms of welfare, market EO is indifferent between curtailing consumers and getting high price imports. Market EO gets an incremental value:

$$\begin{aligned} W_{eo} - W^* =& (\bar{P} - c)\left(\int_0^{k^c_{eo}+T} l f(l) dl + (1 - F(k_{eo} + T))k_{eo}\right) - r k_{eo} + (1-\alpha)(\bar{P} - c)T(F(k^T - T) - F(k^c_{eo} + T)) \\ & - (\bar{P} - c)\left(\int_0^{k^*} l f(l) dl + (1 - F(k^*))k^*\right) - r k^* \end{aligned} \tag{26}$$

with $k^* = k^c_{eo} + T = F^{-1}(\frac{r}{\bar{P}-c})$

$$= T\left(\overbrace{r}^{\substack{\text{Less capacity} \\ \text{to build}}} - \overbrace{(\bar{P} - c)(1 - F(k^i_{eo}))}^{\substack{\text{Incremental high priced imports} \\ \text{or curtailment} \\ \text{(locally available if EO were isolated)}}}\right) + (1-\alpha)(\bar{P} - c)T(F(k^T - T) - F(k^* + T))$$

by free-entry in market EO, the first term cancels out:

$$= (1-\alpha)(\bar{P} - c)T(F(k^T - T) - F(k^*)) \geq 0 \tag{27}$$

In short, market EO builds T less capacity and purchases power from CP when $k_{eo}^i < l_{eo} < k^T$. CP's welfare is augmented as in some states of the world, some otherwise idle capacity can export to EO at high prices. Disregarding congestion rents, or assuming CP owns it, EO's welfare is unchanged as it builds less capacity, but needs to buy more power from CP, and these two effects cancel out. If EO owns some share of transmission rights, its welfare is increased. It is therefore (weakly) mutually beneficial to interconnect the markets. In the reasonable case where the exporters own the transmission rights (whether it is the exporting TSO or the exporting producers) and get the congestion rent ($\alpha = 1$), depending on CP and EO's relative bargaining power, EO could require from CP any amount between 0 and $(\bar{P} - c)\left(T(F(k^T - T) - F(k^*)) + \int_{k^T-T}^{k^T}(k^T - l_{eo})f(l_{eo})dl_{eo}\right)$, as a compensation payment for CP unilaterally implementing a capacity payment.

This may be a consolation prize for the loss in security of supply endured by EO: Before interconnection, the expected curtailment was $\mathcal{L}^* = \int_{k^*}^{1}(l - k^*)f(l)dl$. After interconnection it becomes:

$$\mathcal{L}_{eo} = \int_{k^*}^{k^T-T}(l - (k_{eo}^c + T))f(l)dl + \int_{k^T-T}^{k^T}(2l - (k_{eo} + k^T))f(l)dl + \int_{k^T}^{\infty}(l - k_{eo}^c)f(l)dl \tag{28}$$

$$= \mathcal{L}^* + \int_{k^T-T}^{k^T}(l - (k^T - T))f(l)dl + (1 - F(k^T))T > \mathcal{L}^* \tag{29}$$

Thus, proposition 1 can be extended to the case when transmission is binding:

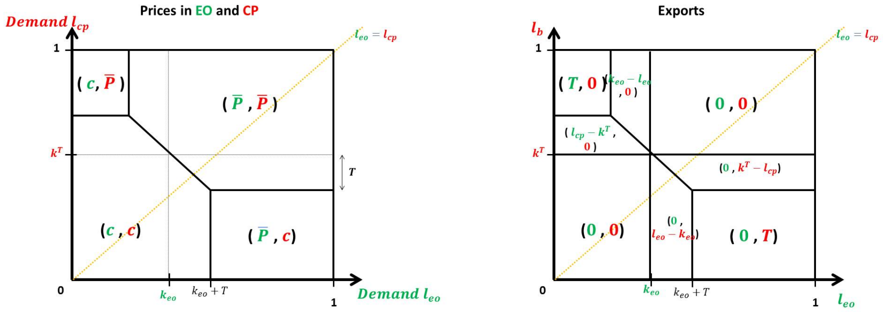
Proposition 2 *If the transmission line is sometimes congested, and depending on the allocation of transmission rights, albeit losing ground from the point of view of security of supply, an energy-only market connected to a market with capacity payment can get additional revenues through congestion rents, translating in an increase in welfare. This is true if and only if the decrease in security of supply in the EO market is not so strong that it forces it to implement a CRM.*

Proof. Follows from previous developments ■

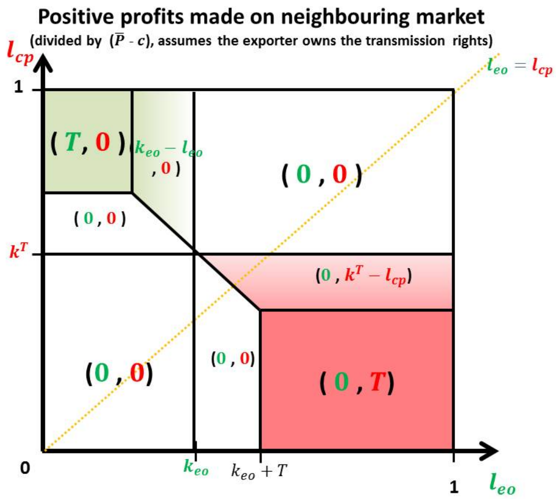
6 Interconnected EO/CP markets – general case

We now relax the assumption that $l_{eo} = l_{cp}$. Thus, l is now bidimensional, and $l = (l_{cp}, l_{eo})$, distributed according to PDF $f(l)$. Name $F_s(.)$ the CDF of the *sum* of both demands: $F_s(K) = \mathbb{P}(l_{cp} + l_{eo} \leq K)$.

Figure 2 shows the equilibrium prices, imports and profits made abroad when CP and EO are interconnected.



(a)



(b)

Figure 2: Prices in market EO and CP (top left), Exports (top right) and profits made abroad (bottom) as a function of demand l_{eo} and l_{cp}. Red (green) areas indicate profits made by CP in EO (EO in CP). In this graph, transmission is never binding if loads are perfectly correlated ($l_{eo} = l_{cp}$).

6.1 Transmission is never binding

Free-entry

Assume that transmission is never binding. By free-entry in the energy-only market, we have that:

$$r = (\bar{P} - c)\,(1 - F_s(k_{cp} + k_{eo})) \tag{30}$$

, as long as $k_{eo} > 0$.

Assuming that the capacity payment in the neighbouring market is m, free-entry in the CRM market yields

$$r = m + (\bar{P} - c)\,(1 - F_s(k_{cp} + k_{eo})) \tag{31}$$

We thus find again that as long as there is still some economically viable capacity in the energy-only market, we have that $m = 0$: CP's CRM comes at zero upfront cost.

Denote K^{eq} the total equilibrium level of capacity: $K^{eq} = k_{eo} + k_{cp} = F_s^{-1}\left(1 - \frac{r}{P-c}\right)$. k_{cp} (and in turn k_{eo}) will be pinned down by CP's SoS target.

Curtailement levels

Assume that absent intervention, capacity in each market (αK^{eq} in CP, $(1-\alpha)K^{eq}$ in EO) is such that the EENS are the same. Assume further that:

$$0 \leq \mathcal{L}_{cp}^T \leq \mathcal{L}_{cp}(\alpha K^{eq}, (1-\alpha)K^{eq}) = \mathcal{L}_{eo}(\alpha K^{eq}, (1-\alpha)K^{eq}) \leq \mathcal{L}_{eo}^T$$

Where the first inequality means curtailment is non negative, the second one means CP's maximum expected curtailment is less than the equilibrium one (hence the need to implement a CRM). The equality states formally that without CRMs, the EENS is the same in both countries. The last inequality means market EO does not need to implement a CRM if CP doesn't.

Optimality requires that CP just meets (and does not exceed) its SoS target $\mathcal{L}_{cp}^T$. There can be some curtailment if (1) both markets are tight or (2) only CP is tight, but the overall system is tight. Thus, we can write:

$$\mathcal{L}_{cp}^T = \mathcal{L}_{cp}(k^T, K^{eq} - k^T) = \iint_{\substack{l_{cp} \geq k_{cp} \\ l_{eo} > k_{eo}}} (l_{cp} - k_{cp}) f(l) dl + \iint_{\substack{l_{eo} \leq k_{eo} \\ l_{cp} + l_{eo} > k_{cp} + k_{eo}}} (l_{cp} - (k_{cp} + k_{eo} - l_{eo})) f(l) dl \tag{32}$$

$$= \iint_{\substack{l_{cp} \geq k^T \\ l_{eo} > K^{eq} - k^T}} (l_{cp} - k^T) f(l) dl + \iint_{\substack{l_{eo} \leq K^{eq} - k^T \\ l_{cp} + l_{eo} > K^{eq}}} (l_{cp} + l_{eo} - K^{eq}) f(l) dl \tag{33}$$

We have that $\mathcal{L}_{cp}(k^T, K^{eq} - k^T)$ monotonically decreases in k^T. $\mathcal{L}_{cp}(\bar{l}_{cp}, K^{eq} - \bar{l}_{cp}) = 0 < \mathcal{L}_{cp}^T$, and $\mathcal{L}_{cp}(\alpha K^{eq}, (1-\alpha)K^{eq}) = \mathcal{L}_{eo}(\alpha K^{eq}, (1-\alpha)K^{eq}) > \mathcal{L}_{cp}^T$. Thus, there exists a unique k^T such that CP meets its maximum expected curtailment target at least cost. k_{eo} is then pinned down by free entry in the energy-only market: $k_{eo} = K^{eq} - k^T$, such that total capacity remains optimal, whatever CP's target is.

Let us now see the impact on EO's expected curtailment, when $k^T \leq K^{eq}$.

$$\mathcal{L}_{eo}(k^T, K^{eq} - k^T) = \iint_{\substack{l_{cp} \geq k^T \\ l_{eo} > k_{eo}}} (l_{eo} - (K^{eq} - k^T))f(l)dl + \iint_{\substack{l_{cp} \leq k^T \\ l_{cp} + l_{eo} > K^{eq}}} (l_{cp} + l_{eo} - K^{eq}))f(l)dl \tag{34}$$

The first term is the expected curtailment when both markets are tight, and the second one means CP is not tight, but its exports are not sufficient for EO to meets its local demand.

One observes that $\mathcal{L}_{eo}(k^T, K^{eq} - k^T)$ monotonically increases in k^T. If $k^T \leq \alpha K^{eq}$ (i.e. CP doesn't need to build a CRM), $\mathcal{L}_{eo}(k^T, K^{eq} - k^T) = \mathcal{L}_{eo}(k^T, K^{eq} - k^T) < \mathcal{L}_{eo}^T$, EO doesn't need to implement a CRM. If $k^T > \alpha K^{eq}$ (i.e. if CP implements a CRM) we have $\mathcal{L}_{eo}(k^T, K^{eq} - k^T) > \mathcal{L}_{eo}(\alpha K^{eq}, (1-\alpha)K^{eq})$. If $k^T = K^{eq}$, we have that $k_{eo} = 0$. Then the expected curtailment in EO is high, as EO relies exclusively on CP's exports. When the target in CP is so large that it exceeds the equilibrium total capacity, ($k^T \geq K^{eq}$) we have:

$$\mathcal{L}_{eo}(k^T, 0) = \iint_{l_{cp} \geq k^T} l_{eo} f(l)dl + \iint_{\substack{l_{cp} \leq k^T \\ l_{cp} + l_{eo} > k^T}} (l_{cp} + l_{eo} - k^T))f(l)dl \tag{35}$$

This expected curtailment is *decreasing* in k^T and can be lower or greater than $\mathcal{L}_{eo}^T$. Note that $\mathcal{L}_{eo}(k^T) \underset{k^T \to \infty}{\to} 0$, meaning if CP's aversion to curtailment is extremely high, EO might actually benefit from it, both in terms of SoS and consumer costs.

Figure 3 gives an illustration of the expected curtailment in EO when CP implements a capacity payment. When the expected curtailment is higher than the target (red area), EO will have to implement a CRM as well.

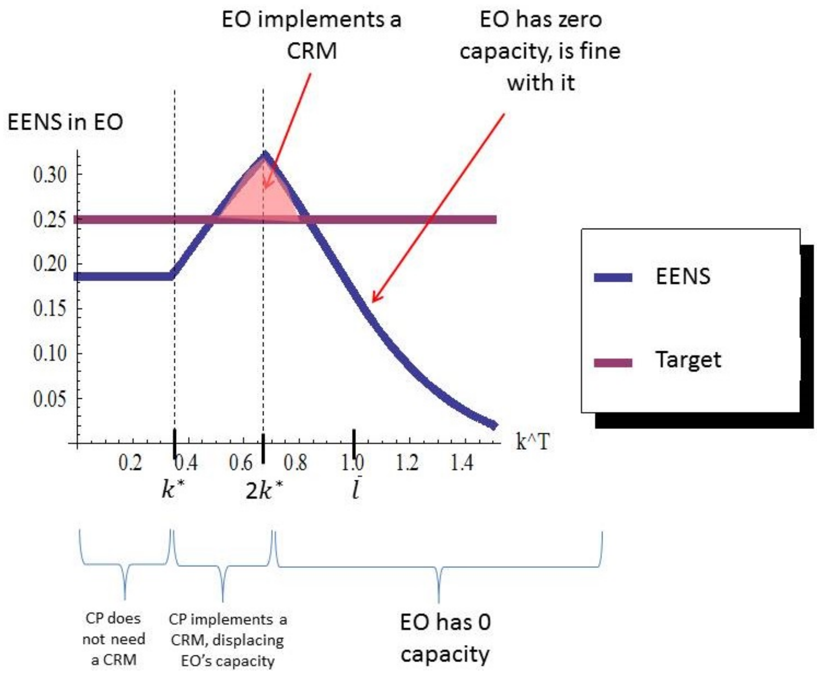


Figure 3: Expected curtailment in EO (blue line) for i.i.d demand following a uniform distribution over $[0, 1]$. Expected curtailment increases with k^T, and then decreases when capacity in EO reaches 0. For some region, EO will be forced to implement a CRM in order to meet its SoS standard (red line, level is arbitrary).
$r = 500$, $c = 50$,$T = \infty$, $\bar{P} = 700$

Welfare analysis

As long as $k^T < K^{eq}$, total capacity in the system is the optimal level K^{eq}. Therefore, the overall system remains optimal and only the allocation of social welfare between EO an CP will be affected.

Welfare in market CP can be calculated as:

$$W_{cp} = \overbrace{(\bar{P} - c) \iint_{l_{cp} + l_{eo} \leq K^{eq}} l_{cp} f(l) dl}^{no\ overall\ scarcity} \tag{36}$$

$$+ (\bar{P} - \bar{P}) \left(\iint_{\substack{l_{cp} \leq k^T \\ l_{cp} + l_{eo} \geq K^{eq}}} l_{eo} f(l) dl + \iint_{\substack{l_{cp} \geq k^T \\ l_{eo} \geq K^{eq} - k^T}} k^T f(l) dl + \iint_{\substack{l_{eo} \leq K^{eq} - k^T \\ l_{cp} + l_{eo} \geq K^{eq}}} (K^{eq} - l_{eo}) f(l) dl \right) \tag{37}$$

$$- k^T * m \tag{38}$$

given that $m = 0$:

$$= (\bar{P} - c) \iint_{l_{cp} + l_{eo} \leq K^{eq}} l_{cp} f(l) dl \tag{39}$$

Again, notice that CP's welfare does not depend on k^T, while demand coverage has increased: the support scheme comes at no welfare cost!

Given that total welfare is insensitive to k^T, we can verify that welfare in market EO is also insensitive to k^T:

$$W_{eo} =(\bar{P}-c)\iint_{l_{cp}+l_{eo}\leq K^{eq}} l_{eo}f(l)dl \tag{40}$$

$$+(\bar{P}-\bar{P})\left(\iint_{\substack{l_{cp}\leq k^T\\ l_{cp}+l_{eo}\geq K^{eq}}} K^{eq}-l_{cp}f(l)dl+\iint_{\substack{l_{cp}\geq k^T\\ l_{eo}\geq K^{eq}-k^T}} K^{eq}-k^Tf(l)dl+\iint_{\substack{l_{eo}\leq K^{eq}-k^T\\ l_{cp}+l_{eo}\geq K^{eq}}} l_{eo}f(l)dl\right) \tag{41}$$

$$=(\bar{P}-c)\iint_{l_{cp}+l_{eo}\leq K^{eq}} l_{eo}f(l)dl \tag{42}$$

CP's CRM does not modify EO's welfare, but decreased its SoS level. If $\mathcal{L}_{eo}(k^T,k_{eo})>\mathcal{L}_{eo}^T$, EO will implement a CRM as well. It can be either a strategic reserve or some form of capacity payment. Those cases are discussed in the next section.

The main conclusion of this two subsections can be summarized as follows:

Proposition 3 *If a market unilaterally implements a capacity payment and transmission capacity is never biding, a neighbouring energy-only market endures a capacity decrease, equivalent to the incremental capacity in the capacity payment market. Welfare is unchanged, but SoS decreased.*

Proof. Follows from previous developments ■

6.2 Transmission is binding

So far, I've assumed that the transmission line was never congested. However, a transmission line with an optimal size should be congested sometimes, so that the fixed costs of investment in transmission are recovered through the congestion rent. Assume now that transmission can be congested, i.e. $\mathbb{P}(l_{cp}-k_{cp}>T\ \cap\ k_{eo}-l_{eo}>T)+\mathbb{P}(l_{eo}-k_{eo}>T\ \cap\ k_{cp}-l_{cp}>T)>0$.

Free entry conditions are:

$$r = \left(\bar{P} - c\right) \left(\iint_{\substack{k_{eo} + T < l_{eo} \\ l_{cp} \leq k_{cp} - T}} f(l)dl + \iint_{\substack{l_{eo} \geq k_{eo} - T, l_{cp} \geq k_{cp} - T \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \right) \tag{43}$$

$$r = \left(\bar{P} - c\right) \left(\iint_{\substack{k_{cp} + T < l_{cp} \\ l_{eo} \leq k_{eo} - T}} f(l)dl + \iint_{\substack{l_{eo} \geq k_{eo} - T, l_{cp} \geq k_{cp} - T \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \right) + m \tag{44}$$

$$\Rightarrow m = \left(\bar{P} - c\right) \left(\iint_{\substack{k_{eo} + T < l_{eo} \\ l_{cp} \leq k_{cp} - T}} f(l)dl - \iint_{\substack{k_{cp} + T < l_{cp} \\ l_{eo} \leq k_{eo} - T}} f(l)dl \right) > 0 \tag{45}$$

As a consequence of limited transmission capacity, capacity in CP is no longer a perfect substitute toEO's capacity, and CP will enjoy less high-priced exports. Therefore CP's TSO has to give a positive amount of support to capacity.

Equilibrium capacities will be set by equation 43 and CP's SoS level. Keeping in mind that, thanks to equation (43), k_{eo} is a function of $k_{cp} = k^T$:

$$\mathcal{L}_{cp}^T = \mathcal{L}_{cp}(k^T, k_{eo}(k^T)) = \iint_{\substack{l_{cp} \geq k^T \\ l_{eo} > k_{eo}}} (l_{cp} - k^T) f(l)dl + \iint_{\substack{k_{eo} - T \leq l_{eo} \leq k_{eo} \\ l_{cp} + l_{eo} > k^T + k_{eo}}} (l_{cp} - (k^T + k_{eo} - l_{eo})) f(l)dl \tag{46}$$

$$+ \iint_{\substack{l_{eo} \leq k - T \\ l_{cp} > k^T + T}} (l_{cp} - (k^T + T)) f(l)dl \tag{47}$$

Unfortunately the system of equations (43,45,47) has no closed-form solution. Figure 4 is equivalent to figure 3, but with a transmission line that can be congested. For a given level of SoS in CP, SoS in EO is higher than in the "no congestion" case, as limited capacity protects EO's plants from CP's competition: A smaller transmission line means it is less likely that the energy-only neighbour will have to implement a CRM. In fact, for very small transmission capacity, and an energy-only market that's far enough from its expected curtailment limit, interconnection will have no welfare impact on the energy-only market. On top of that, if market EO gets at least a small part of the congestion rent, interconnection provides additional revenues to the energy-only market, translating in a welfare increase compared to an isolated or EO/EO case.

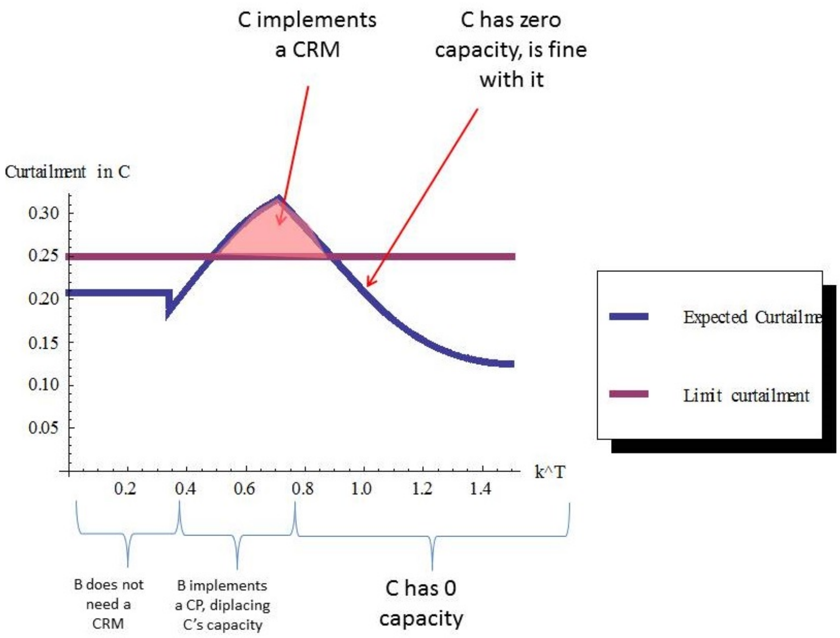


Figure 4: Expected curtailment in EO (blue line) for i.i.d demand following a uniform distribution over $[0, 1]$. Expected curtailment increases with k^T, and then decreases when capacity in EO reaches 0. Transmission capacity T is 0.2. For some SoS levels in CP, EO will be forced to implement a CRM in order to meet its SoS standard (red line, level is arbitrary).
$r = 500$, $c = 50$, $\bar{P} = 700$

7 Fight-back strategies

Given that an ernergy-only market will likely be prejudiced if its neighbour implements a capacity payment, what are the possible responses of the EO regulator or TSO? We explore below three potential initiatives.

7.1 Control imports

An TSO could in theory control all imports, or the expensive ones only ($p = \bar{P}$), or the cheap ones only ($p = c$). Controlling all imports would be a sensible solution, as we have already proved that welfare in the EO market is unchanged post-disconnection, but SoS increases. However, this goes against the security of supply directive, and the current drive to open-trade in Europe. Then, consumers' or political pressure means it seems unlikely that a TSO will withstand the temptation to import cheap electricity when prices would otherwise be high.

Curtailing imports only when they are cheap ($p = c$) would make little sense, as a TSO aims at minimizing costs, and won't be able to get electricity at a price lower than marginal cost. The foreign market does not extract any profits from selling at marginal cost, meaning the investments incentives in CP and EO are unchanged.

Let us now investigate the case when a TSO would curtail high-priced exports only. A first comment is that it would be a bold measure: in the short term, curtailing high-priced imports would simply result in more curtailment. Even though welfare is unchanged (with price at VoLL, a consumer is indifferent between being curtailed and paying for electricity), curtailment increases.

Let us turn now to the long-run effects. Note that the price signals in EO is unaffected by import curtailment. then, notice that the target capacity in CP is not modified compared to the "laissez faire" case: $k_{cp} = k^T$, as EO's import curtailment does not affect expected consumer curtailment in CP: Capacity investments in either markets will be unaffected by the measure. Free-entry in CP yields:

$$m = r - (\bar{P} - c) \left(\overbrace{\mathbb{P}(l_{cp} > k^T + T, l_{eo} < k^*)}^{\substack{\textit{Transmission congested in} \\ EO \rightarrow CP \textit{ direction}}} + \overbrace{\mathbb{P}(l_{cp} > k^T, l_{eo} > k^* - T, l_{cp} + l_{eo} > k^T + k^* - T}^{\substack{CP \textit{ and overall} \\ \textit{system are congested}}} \right) \tag{48}$$

Note that the capacity payment is now greater than what we found when EO did not control imports.

However, investment in the energy-only market is unchanged, as prices hit the cap in the very same states of the world as in the no-control case. Thus, such a policy is welfare-neutral for EO, but results in increased curtailment, with no effect on investment incentives. Overall welfare decreases, as CP's capacity is used inefficiently.

A wiser policy, but somewhat more interventionist, would be that import be managed by a national benevolent planner (maximizing its own market's welfare). That is, the planner would buy on a foreign market its missing supply *up to* the foreign's market capacity margin. That is, EO's planner would buy a quantity $Q = Min(l_{eo} - k_{eo}, k_{cp} - l_{cp} - \epsilon)$, ensuring it procures imports at marginal cost. In this setting, if the planner resells at market prices on its own market, market EO would recover all the cross-border rent CP was extracting from EO and capacity in both markets would recover their optimal level. This way, EO still endures increased curtailment due to CP's CRM, but enjoys decreased system costs.

At any rate, these national controls on imports seem to go strongly against the European Commission's guidelines, and will likely be challenged.

Proposition 4 *A prejudiced TSO might respond by forbidding imports. However, only the (unlikely)* *"curtail all imports" or "national procurement" paradigms allow to recover the energy-only's security of supply level without implementing an explicit CRM on its own.*

Proof. Follows from previous developments ■

7.2 Implement a CRM as well: CP or SR?

Assume that CP's capacity payment endangered EO's security of supply: $\mathcal{L}_{eo}(k^T, k_{eo}(k^T)) > \mathcal{L}_{eo}^T$. Then, the EO market will have to implement a CRM as well. The question is, should it implement it in the form of a strategic reserve, or a capacity payment?

Assume EO wants to increase its SoS by a given level. From the point of view of SoS, whether it uses a SR or a CP does not matter: local demand has priority over local generation anyways. Then, this extra capacity will, as a side-effect, improve the neighbours' SoS as well: if EO increases its capacity by δ, CP will decrease its capacity by $\delta' < \delta$. Again whether EO has a SR or a CP has the same impact on CP's SoS (and in turn, on CP's capacity target).

The welfare costs of capacity support, assuming EO wants to increase local capacity by a small δ is:

$$-\Delta W_{sr} = r\delta - (\bar{P} - c)(\overbrace{\Delta\mathcal{L}_{eo}}^{Incremental\ coverage} + \overbrace{\Delta\mathcal{L}_{cp}}^{high-priced\ exports}) \tag{49}$$

$$\tag{50}$$

Given that EO's gross welfare is the same whether it implements a SR or a CP to meet its target (gross welfare is: $VoLL * covered\ demand$), we just need to compare costs. In both cases EO has to finance $r\delta$ capacity, a cost that will be either covered by an upfront payment on consumers' bills, or high electricity prices. The only thing that matters is how much profits/expenses are made abroad.

The flow and price pattern will differ only in states of the world where $k_{sr} + k^T = K^{eq} \leq l_{sr} + l_{cp} \leq k_{sr} + \delta + k^T - \delta'$. In this range, a SR sells at high prices to CP when $l_{cp} \geq k^T - \delta'$, such that demand in CP is met, but with high-priced imports. On the other hand, CP is making profits by undercutting SR's strategic reserve when $l_{cp} \leq k_T - \delta'$.

Thus, when EO implements a SR instead of a CP, there are some incremental cross-border rent extraction from EO towards CP:

$$\Delta RE(k_{sr}+\delta, k^T-\delta') = (\bar{P}-c)\Big(\iint_{\substack{k^T+k_{sr}\le l_{sr}+l_{cp}\le k^T+k_{sr}+\delta-\delta' \\ k^T-\delta'\ge l_{cp}}} (k^T-\delta'-l_{cp})f(l_{sr},l_{cp})dl_{sr}dl_{cp} \tag{51}$$

$$-\iint_{\substack{k^T+k_{sr}\le l_{sr}+l_{cp}\le k^T+k_{sr}+\delta-\delta' \\ k^T-\delta'\le l_{cp}}} (l_{cp}-(k^T-\delta'))f(l_{sr},l_{cp})dl_{sr}dl_{cp}\Big) \tag{52}$$

The cost difference between implementing a SR or a CP is $\Delta RE(k_{sr}+\delta, k^T-\delta') > 0$[9]: To maintain its SoS, an Energy-only market should implement a capacity payment instead of a strategic reserve. Appendix L discusses the required level of payment in EO when there are market frictions.

7.3 EO switches to a capacity payment: here comes the free-riding

We saw in the previous section that if EO has to implement some capacity support, he should do it through a capacity payment, and not a strategic reserve. In this section, we'll see that it might actually be *profitable* for EO to increase slightly its capacity through a payment, even absent any consideration on SoS.

Assume for simplicity that EO and CP are symmetric, as in section 5. However market "EO" also has a target k_{ep}^T. The free-entry condition (equivalent to 15 and 16) are:

$$Market\ CP: \quad r = m_{cp} + (\bar{P}-c)\left(1-F\left(\frac{k^T+k_{eo}^T}{2}\right)\right) \tag{53}$$

$$Market\ EO: \quad r = m_{eo} + (\bar{P}-c)\left(1-F\left(\frac{k^T+k_{eo}^T}{2}\right)\right) \tag{54}$$

Thus we must have that $m_{eo} = m_{cp} = (\bar{P}-c)\left(F\left(\frac{k^T+k_{eo}^T}{2}\right) - F(k^*)\right)$. Welfare in EO, if it reaches capacity k_{eo}^T is :

$$W_{eo}(k^T, k_{eo}^T) = (\bar{P}-c)\int_0^{\frac{k^T+k_{eo}^T}{2}} lf(l)dl + (\bar{P}-\bar{P})\int_{\frac{k^T+k_{eo}^T}{2}}^{k^T} lf(l)dl + (\bar{P}-\bar{P})\left(1-F(k^T)\right)k^T - m_{eo} * k_{eo}^T \tag{55}$$

$$= (\bar{P}-c)\left(\int_0^{\frac{k^T+k_{eo}^T}{2}} lf(l)dl - \left(F\left(\frac{k^T+k_{eo}^T}{2}\right) - F(k^*)\right)k_{eo}^T\right) \tag{56}$$

$$= W^* + (\bar{P}-c)\left(\int_{k^*}^{\frac{k^T+k_{eo}^T}{2}} lf(l)dl - \left(F\left(\frac{k^T+k_{eo}^T}{2}\right) - F(k^*)\right)k_{eo}^T\right) \tag{57}$$

[9] when markets are symmetric

Note first that this formula is consistent with our previous findings. If the EO market does not try to maintain any target (i.e. $k_{eo} = 2k^* - k^T$), then $W_{eo}(k^T, 2k^* - k^T) = W^*$. If the EO market decides to implement the same reliability level as market CP (i.e. $k_{eo} = k^T$), both markets become perfectly symmetric, and there are no longer any gains from trade: $W_{eo}(k^T, k^T) = W_{cp}(k^T, k^T) = W^i_{cp}(k^T) < W^*$.

However some intermediate target might be welfare-improving in EO:

$$\frac{\partial W_{eo}}{\partial k_{eo}}(k^T, k_{eo}) = (\bar{P} - c)\left[\frac{k^T - k_{eo}}{4} f\left(\frac{k^T + k_{eo}}{2}\right) - \left(F\left(\frac{k^T + k_{eo}}{2}\right) - F(k^*)\right)\right] \tag{58}$$

Observe that $\frac{\partial W_{eo}}{\partial k_{eo}}(k^T, 2k^* - k^T) \geq 0$, meaning that increasing capacity slightly through a capacity payment is welfare-improving compared to the "no regulatory reaction" case. The optimal level of capacity in EO, even absent SoS concerns, is in $]2k^* - k^T, k^T[$. Indeed, EO does not take into account that its capacity support will increase the capacity payment in market CP. Therefore, there will be over-investment in capacity overall.

8 Discussion

8.1 The "cross-border solidarity" sharing rule

Assume that TSOs surrender their preference for local consumers, and they agree to arrange flows so that the magnitude of curtailment is the same in both market: if total demand exceeds total capacity by 2 MW, each market will curtail 1MW, independent of where capacity is located.

If transmission is not binding, the free-entry conditions (30) and (31) still apply. Indeed, in our model, prices and thus investment incentives are independent from the sharing rule: prices hit the price cap if and only if the (integrated) market is tight. Given that there is no creation of capacity, demand is unchanged and the CRM is costless and useless: by definition of the sharing rule, the EENS will be the same in both countries. In that case, and with solidarity between markets, CRM are irrelevant unless they are jointly implemented.

As in section 6.2, things get more complicated when transmission is binding. TSOs can ensure that demand is equally curtailed only if the transmission capacity allows it. Again, the free-entry conditions (43) to (45) still hold. As in the "national preference" case (see section 6.2), the capacity payment is positive and there is indeed creation of capacity. Thus, the market with a CRM will indeed enjoy additional demand coverage. When demands are symmetric, and markets commit to solidarity, the SoS in the market with no CRM is unaltered: we've seen that capacity in the no-CRM market reaches $k^* - T$. When demand exceeds local capacity, the no-CRM market imports up to T. Even when both markets are tight, the market with a CRM continues to send T to the no-CRM market (since $l - (k^T - T) > l - (k_{eo} + T)$ by definition of the transmission capacity being binding) and the no-CRM market still enjoys $k_{eo} + T = k^*$ available capacity at all times, as if there were no CRM at all. Thus, any additional demand coverage will occur in the market with a CRM. How much is created has no impact on the neighboring market, as the transmission line gets congested anyway. Thus, when transmission is binding, the "European solidarity" paradigm allows CRMs to be both relevant *and* have no cross-border welfare or SoS impact. However, it requires a strong displacement of capacity from the market with no-CRM to the market with a CRM.

When demands are symmetric, the impact of a unilaterally-implemented CRM to reach a given level of local demand coverage, on the regional (left part of the parenthesis) and cross-border demand coverage (right part) can be summarized in the table below:

paradigm / transmission	National preference	European solidarity
Binding	$\big($positive, negative$\big)$	$\big($positive, $\emptyset\big)$
Non binding	$\big(\emptyset$, negative (large)$\big)$	$\big(\emptyset, \emptyset\big)$

Table 4: The LHS is the effect of unilateral implementation of a CRM on regional demand coverage, and RHS is its cross-border effect on demand coverage

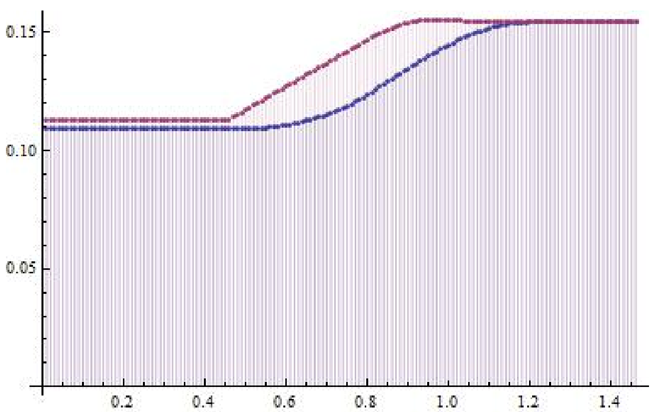


Figure 5: EENS in a market with no CRM, as a function of its (with-CRM) neighbour's capacity target k_{cp}. Purple dots show EENS when TSOs follow the national preference paradigm, blue dots show EENS when TSOs commit to cross-border solidarity. $T = 0.1$,$\bar{P} = 1200$,$c = 100$,$r = 500$, demand is uniformly distributed and i.i.d.

With asymmetric demands, numeric applications as the one shown in figure 5 suggest the following table:

paradigm / Transmission	National preference	European solidarity
Binding	(positive, negative)	(positive, negative (small))
Non binding	($\emptyset$, negative (large))	($\emptyset, \emptyset$)

Table 5: The LHS is the effect of unilateral implementation of a CRM on regional demand coverage, and RHS is its cross-border effect on demand coverage

This leads to the following conclusions:

- Whether transmission is binding or not, the "European solidarity" paradigm mitigates the negative cross-border effects on security of supply.
- TSOs implementing a capacity payment will have a strong incentive to control exports, as it increases their SoS at a small costs, by decreasing neighbours' SoS. If they secure the right to control exports, they will likely want to increase transmission capacity so that they can enjoy a strong business stealing effect.
- If a regional TSO manages to enforce European solidarity, a unilateral CRM is useless unless transmission is binding. Local TSOs willing to implement a CRM will have an increased incentive to under-size transmission capacities, in order to isolate their markets as much as possible.

8.2 Extensions

This work can be extended in at least two obvious directions. First, an empirical analysis should be carried out to understand the magnitude of the cross-border investment effect, and the extent to which a foreign market is affected by neighbouring supported capacity. This will allow to estimate which market players should participate in CRMs and whether some compensation to neighbours should be considered. Second, transmission capacity could be endogenized. Taking into account the effects of transmission on capacity equilibrium in the long-run, optimal and equilibrium transmission capacities might differ. A rather surprising result is that, given the potential subsequent decrease in SoS observed in sections 5 and 6, a new TSO might need to *compensate* an EO market for interconnecting it with a market with a capacity payment.

Then, the effects of different price caps, demand response, production intermittency and predictability should be analysed. This model could be used to analyse the impact of subsidized, very low marginal costs renewables on cross-border investment incentives. The [OECD, 2013] and [Felder, 2011] stress that the long-run impacts of renewables on cross-border investments might be significant. We believe much of our previous results would carry over: low marginal cost renewables will provide cheap energy to neighbours in the short-run, leading to a decrease in foreign capacity and SoS in the longer-run. A country with strong RES support might therefore have to indemnify neighbours for the SoS they are deprived of.

9 Conclusion

We start with a benchmark situation where support schemes, implemented in markets without neighbours, are equivalent whether it takes the form of a capacity payment or a strategic reserve. Then, we interconnect markets with different support schemes and observe the cross-border impact of CRMs in the long-run. For a capacity payment to be effective, one needs to have either limited transmission capacity, or that TSOs can control exports. Both solutions seem to be in direct contradiction with the spirit of the Internal Energy Market. If an electricity market unilaterally implements a capacity payment, operational capacity in a neighbouring Energy-only or Energy-only+Strategic Reserve market shrinks. If TSOs are allowed to control exports, those neighbours will be prejudiced and may want to implement a (costly) capacity payment as well, in order to maintain their security of supply standard. Hence, capacity payment schemes may spread in Europe thanks to their negative cross-border externalities on investment. A strategic reserve has no negative cross-border welfare externalities, but neighbours enjoy incremental SoS for free. Only in the case of a capacity support in the form of strategic reserve, can one say that an energy-only neighbour "free-rides" on neighbouring CRM. Our conclusions urge for the harmonization of capacity remuneration schemes across Europe.

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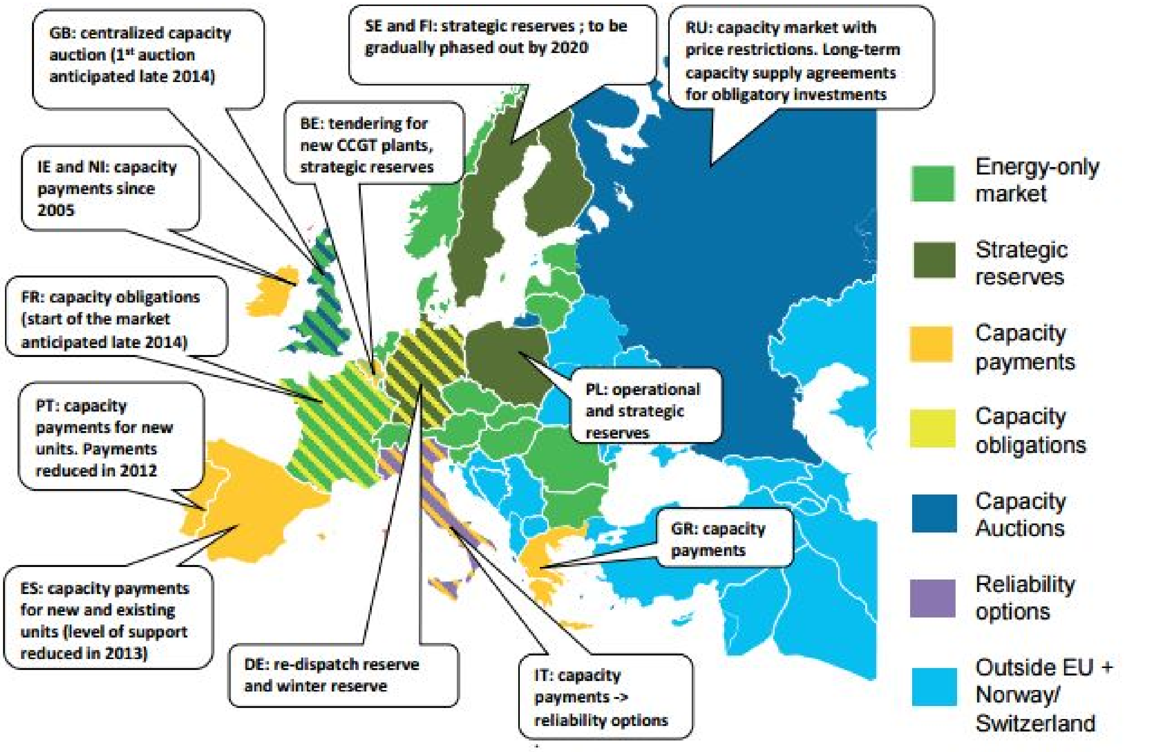
APPENDIX

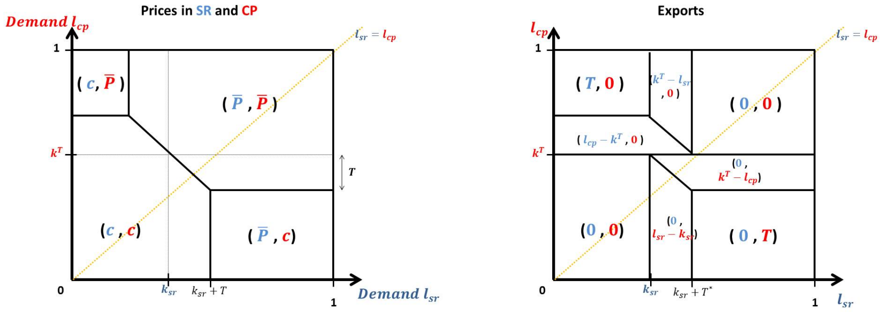
A Scattered national Capacity Remuneration Mechanisms



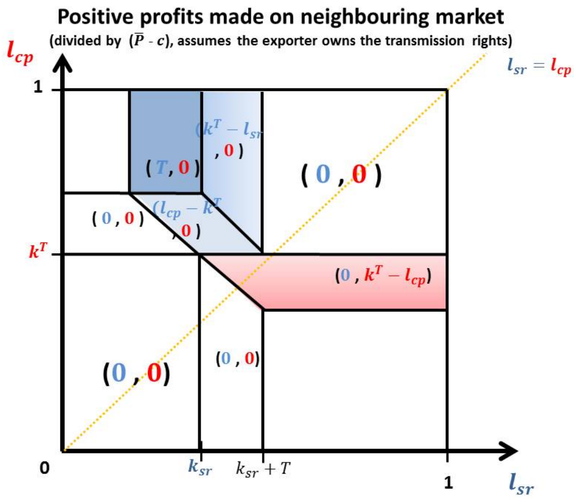
Note: this map is without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.
Source: Eurelectric, 2013.

B Interconnected SR/CP markets – symmetric markets

The price vector $P = (P_{sr}, P_{cp})$, exports and cross-border profits, in the general case where markets are interconnected with a transmission line of capacity T, is given in figure 6.



(a)



(b)

Figure 6: Prices in market SR and CP (top left), Exports (top right) and profits made abroad (bottom) as a function of demand l_{sr} and l_{cp}. Red (blue) areas indicate money transfers from SR to CP (CP to SR).

The key phenomenon we want to highlight is that when demand exceeds operational capacity in SR, but not in CP, CP will export its available generation capacity to SR. If these exports are not sufficient to match SR's demand, prices rise to the cap and SR starts activating its reserve capacity. Then, SR consumers will pay for high-priced imports from CP, while they could in theory use more of SR's reserve capacity that remains idle otherwise. SR's total capacity is under-utilized and there is cross-subsidization (see figure 7).

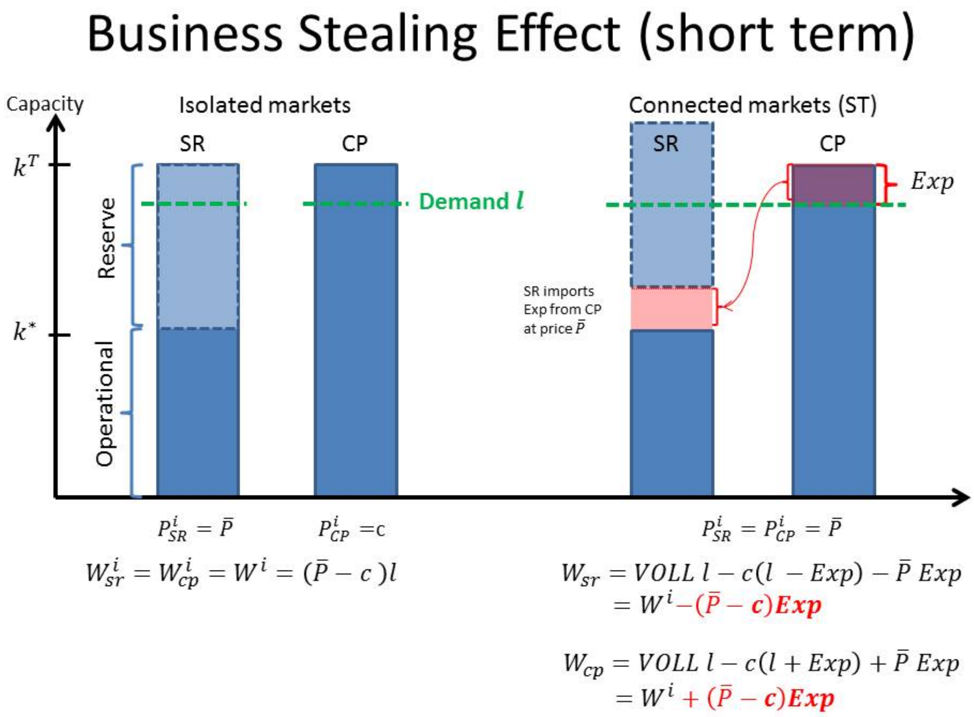


Figure 7: Cross subsidization of CP's capacity payment scheme by SR (strategic reserve)

Let us first investigate the case when demands are correlated, countries have the same SoS target and transmission capacity is very large, and thus never binding. As in the EO/CP case, it happens if and only if $T > \frac{k^T - k_{sr}}{2} \Leftrightarrow T > k^T - k^i_{sr}$.

Transmission is never binding

The price on both market is the same in all states of nature as in the EO/CP case (see table 5.)

Market with a strategic reserve

Free entry yields (recalling $k^T = k_{cp}$):

$$\pi_{sr} = 0 = (\bar{P} - c)\left[1 - F(1/2(k^T + k_{sr}))\right] - r$$

Assume $k^T \leq 2k^i_{sr}$. We have that $k_{sr} = 2F^{-1}(1 - \frac{r}{\bar{P}-c}) - k^T = 2k^i_{sr} - k^T < k^*$: more strategic reserve will need to be provided for by consumers[10]. The payment by consumers for the strategic

[10] in fact, as we'll see later, the costs of the strategic reserve will double: the required capacity is twice what it used to be in the isolated case: $k^{SR}_{sr} = k^T - k_{sr} = 2(k^T - k^i_{sr}) = 2k^{i,SR}_{sr}$

reserve is:

$$CP_{sr} = r(k^T - k_{sr}) - (\bar{P} - c)\left(\int_{1/2(k^T+k_{sr})}^{k^T} (2l_{sr} - k^T - k_{sr}) f(l_{sr}) dl_{sr} + (1 - F(k^T)(k^T - k_{sr})\right)$$

Payments by consumers on the energy market is :

$$CM_{sr} = c \int_0^{\frac{k^T+k_{sr}}{2}} l_{sr} f(l_{sr}) dl_{sr} + \bar{P} \int_{\frac{k^T+k_{sr}}{2}}^{k^T} l_{sr} f(l_{sr}) dl_{sr} + \bar{P} F(1 - k^T) k^T$$

Total consumer payment is :

$$C_{sr} = CP_{sr} + CM_{sr} = rk^T + c(1 - F(k^T)k^T + c \int_0^{\frac{k^T+k_{sr}}{2}} l_{sr} f(l_{sr}) dl_{sr} + c \int_{\frac{k^T+k_{sr}}{2}}^{k^T} l_{sr} f(l_{sr}) dl_{sr} \quad (59)$$

$$- rk_{sr} - (\bar{P} - c)\left(\int_{1/2(k^T+k_{sr})}^{k^T} (2l_{sr} - k^T - k_{sr}) f(l_{sr}) dl_{sr} - (1 - F(k^T)k_{sr}\right) - \bar{P}(1 - F(k^T)k^T \quad (60)$$

$$+ (\bar{P} - c) \int_{\frac{k^T+k_{sr}}{2}}^{k^T} l_{sr} f(l_{sr}) dl_{sr} + \bar{P} F(1 - k^T) k^T \quad (61)$$

$$= C^i_{eo,cp} - (\bar{P} - c)\left[(1 - F(\frac{k^T + k_{sr}}{2}))\right] k_{sr} - (\bar{P} - c)\left(\int_{\frac{k^T+k_{sr}}{2}}^{k^T} (l_{sr} - k^T - k_{sr}) f(l_{sr}) dl_{sr} - (1 - F(k^T))k_{sr}\right) \quad (62)$$

$$= C^i_{sr,cp} + (\bar{P} - c)\left[- \int_{\frac{k^T+k_{sr}}{2}}^{k^T} (l_{sr} - k^T - k_{sr}) f(l_{sr}) dl_{sr} - \left(F(k^T) - F(\frac{k^T + k_{sr}}{2})\right) k_{sr}\right] \quad (63)$$

$$= C^i_{sr,cp} + (\bar{P} - c) \int_{\frac{k^T+k_{sr}}{2}}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr} \quad (64)$$

Recalling that $\frac{k^T+k_{sr}}{2} = k^*$, we observe that the cost increment corresponds to the welfare cost of SoS found in F: the cost of SoS is now twice what it used to be when SR was isolated!

It is easy to check that demand coverage in SR is the same as in the isolated case. Social welfare is thus:

$$W_{sr} = W^i_{sr} - (\bar{P} - c) \int_{\frac{k^T+k_{sr}}{2}}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr} \quad (65)$$

$$= W^*_{eo} - 2(W^*_{eo} - W^i_{sr}) \quad (66)$$

We have assumed here that $k^T \leq 2k^i_{sr}$, such that operational capacity in SR is non-negative. In the limit case $k^T = 2k^i_{sr}$, we habe $k_{sr} = 0$: the market does not build any capacity, and all capacity needs to be provided for by the TSO. We just saw that welfare in SR was reduced. However, appendix H shows that a necessary (not sufficient) condition for the SR/CP integration to increase welfare in SR, is that (1) $k^T > 2k^i_{sr}$ and (2) $k_{sr} = 0$, such that there is no "market" capacity in SR, but the capacity excess in CP is so large that SR meets its SoS target anyways.

Market with a capacity payment

Free entry yields

$$\Pi_{cp} = 0 = m + (\bar{P} - c)\left[(1 - F(\frac{k_{cp} + k_{sr}}{2}))\right] - r$$

Comparing with free-entry in market SR, we find that $m = 0$. Consumers' payment on the energy market are equal to those calculated previously (the uncongested transmission makes sure prices are convergent across markets). The same calculations as in the EO/CP case yield

$$W_{cp} = W^*_{eo}$$

Note again that CP's consumers enjoy the same demand coverage as in the non-integrated case with CP, but costs are the same as in the Energy-only situation: the CP scheme is fully financed through exports to SR. In SR, the capacity (and costs) of the strategic reserve doubled!

Social welfare in CP is :

$$W_{cp} = W^i_{sr} + (\bar{P} - c)\int_{\frac{k_{cp}+k_{sr}}{2}}^{k_{cp}} (k_{cp} - l_{sr})f(l_{sr})dl_{sr} \tag{67}$$

$$= W^*_{eo} \tag{68}$$

$$= W_{sr} + 2\Delta W^i(k^T) \tag{69}$$

Figure 8 illustrates what happens in the short and longer term, when SR and CP get interconnected.

Unsurprisingly, the total welfare remains unchanged compared to the isolated case: there is still a need to build $2k^T$ total capacity at price r per unit, and demand is satisfied/curtailed in the very same states of the world as when markets were separated. Only which consumers will be curtailed has changed.

However consumers from market SR pay more than those in market CP, as the reserve capacity does not sell any energy in market CP, while market CP's capacity sells into market SR, when SR's *operational* capacity is insufficient (even though SR's *total* capacity may be sufficient to meet local demand).

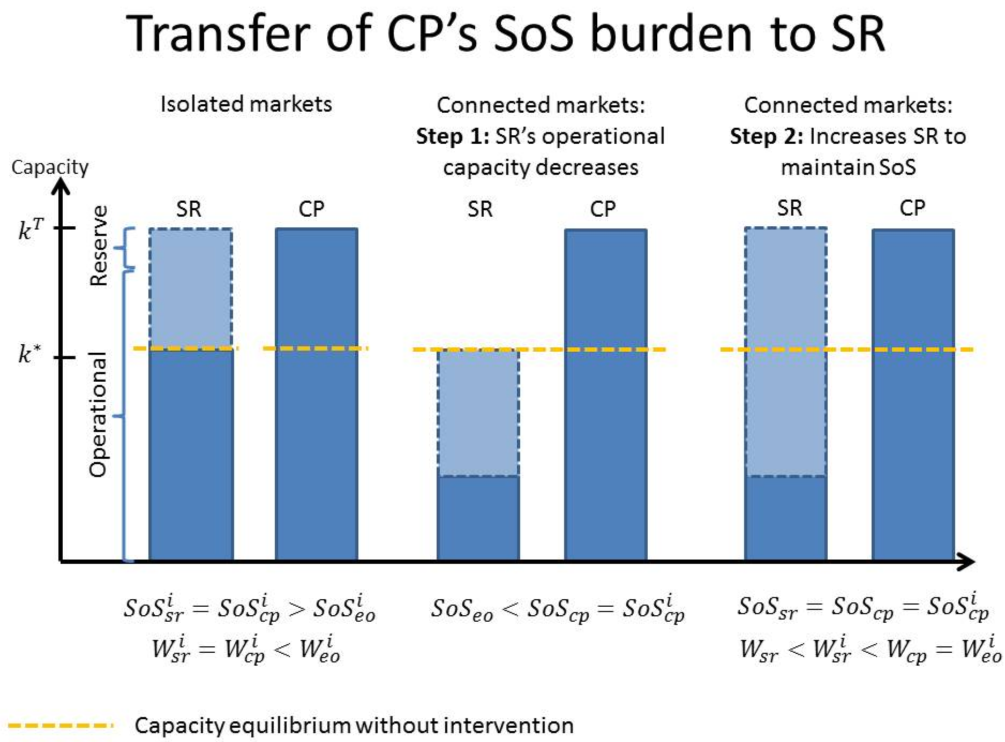


Figure 8: In the long run, SR will bear the cost of CP's capacity payment scheme

Cost of SoS

In this subsection, we relax the assumption that SR and CP have the same SoS standards: Now we allow $k^T_{cp} \neq k^T_{sr} = k^T$. We showed that the marginal social cost of capacity in SR, is weakly greater than in the isolated case. Let's go into more details. When the capacity target k^T is very low or very high, the marginal cost of extra capacity in SR remains unchanged, as either the market alone provides the capacity (very low target, SR remains energy-only without a strategic reserve), or the marginal capacity is used only when both markets are constrained and there are no transmission flows anyway[11] (very high target, exceeding CP's). For intermediate levels of capacity target, the overall social cost is greater than in the isolated case. First, interconnection with CP depresses SR prices, and therefore investment in market SR: $k_{sr}(k^T)$ is a decreasing function of k^T . If $k_{sr}(k^T) < k^T < k^i_{sr}$, SR will have to back up reserve capacity, while it didn't need to intervene when markets were isolated[12]. More precisely, if $k_{sr}(k^T) < k^T < k^i_{sr}$, the last unit of reserve capacity is called only when *total* demand exceeds *total* capacity. The marginal unit is therefore less frequently used than a unit that would be

[11]here we implicitly assume that SR curtails exports before it activates its strategic reserve. If SR were maintaining exports, SR would increase CP's SoS, and in turn CP would decrease its capacity target. This relaxation of a neighbours capacity needs is tackled in the next section and in appendix. Furthermore, a priority rule over SR vs exports is useful only if SR's capacity target exceeds CP's. However, a strategic reserve is often considered as the simplest capacity remuneration scheme, and is therefore likely to be implemented in countries with a smaller adequacy problem, that is, with a low capacity target.

[12]note that the same holds for market EO if $k_{eo}(k^T) < k^T_{eo} < k^*$

called when local demand exceeds local capacity.

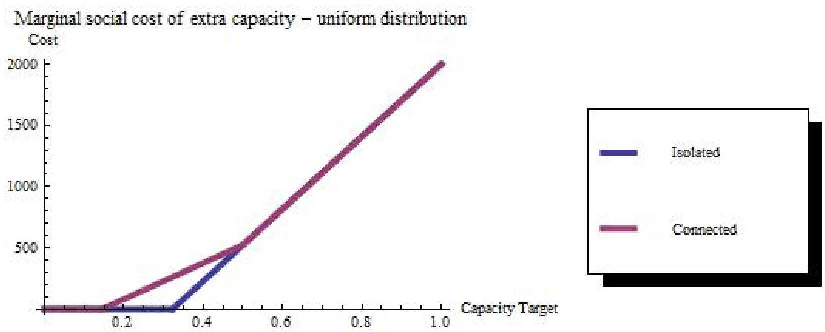
In short, an interconnection with CP may force SR to implement a strategic reserve to meet its adequacy target, and this comes at a higher cost than when the markets were isolated. Interestingly, the cost of capacity in CP is exactly 0, as long as operational capacity in SR k_{sr} exceeds 0[13]. Indeed, even the smallest subsidy for capacity in CP makes it more competitive than market SR's operational capacity: the latter is displaced by the former.

Figure 9 shows SR's marginal cost of capacity is greater for intermediate levels of capacity.

Marginal social cost of an additional unit of reserve capacity:

$$-\frac{\partial W_{sr}}{\partial k^T} = \begin{cases} 0 & \text{if } k^T < k_{sr} \\ r - (\bar{P} - c)\left[1 - F(\frac{k_{cp}+k^T}{2})\right] & \text{if } k_{sr} \leq k^T \leq k_{cp} \\ r - (\bar{P} - c)\left[1 - F(k^T)\right] & \text{if } k^T > k_{cp} \end{cases} \tag{70}$$

$$\geq -\frac{\partial W^i_{sr}}{\partial k^T} = \begin{cases} 0 & \text{if } k^T < k^i_{sr} \\ r - (\bar{P} - c)[1 - F(k^T)] & \text{if } k^T \geq k^i_{sr} \end{cases} \tag{71}$$

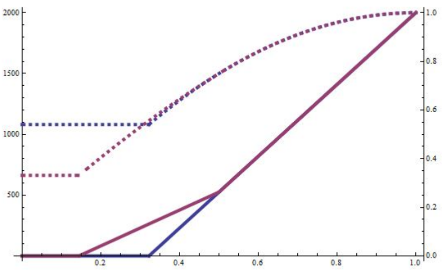


(a)

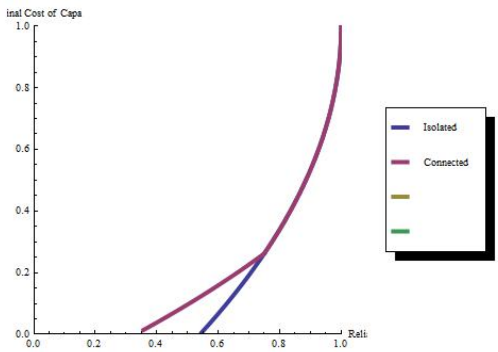
Figure 9: Marginal social cost of extra strategic reserve in SR (connected with EO), when demand follows a uniform distribution on [0, 1].
$r = 2000$, $\bar{P} = 3000$, $c = 50$, $k_{cp} = 0.5$

Figure 10 relates the cost of capacity to demand coverage. First graph shows that integrating an EO market with a CP markets leads to a decrease in demand coverage (dotted lines) in the EO market. It can thus be forced to implement a form of capacity support. In the case of an interconnection between a SR and CP market, the cost of support for capacity increases. The bottom graph shows that if a regulator in an EO market wants to support capacity to compensate for the loss of reliability following interconnection, the cost of reliability is greater than in the isolated case.

[13]that is, k_{cp} is less than twice the equilibrium capacity in an isolated EO market



(a)



(b)

Figure 10: Top: Marginal cost of capacity (solid line, LHS axis) and demand coverage (dashed, RHS axis) as a function of target capacity in a market with SR integrated with a CP market. Bottom: Marginal cost of the last unit of capacity, as a function of demand coverage Uniform distribution, Blue=Isolated, Purple=Connected $r = 2000$,$\bar{P} = 3000$,$c = 50$, $k_{cp} = 0.5$

The conclusions of this subsection can be summarized in the following proposition:

Proposition 5 *When a market with a strategic reserve is interconnected with a symmetric market, where the capacity target is achieved through a capacity payment, the latter market meets its SoS target at zero welfare cost, transfering the burden to the strategic reserve neighbour. Overall welfare is unchanged.*

Transmission is binding

When demand is high, non-reserved capacity in market SR will be insufficient to match demand. In that case market CP will export to SR, possibly until transmission capacity is congested. Price in market SR then jumps to $\bar{P}$. In that case transmission capacity owners get $\bar{P} - c$ by transported unit of electricity. If those owners happen to be CP's firms or CP's TSO, this extra source of revenue is used to decrease the required capacity payments in CP and alleviate consumers bill. Market CP is better off than market SR, even when transmission capacity is small.

Assuming T is small enough so that it is sometimes binding ($T < \frac{k^T - k_{sr}}{2}$), the expected energy profit per unit of capacity is:

$$\pi_{sr} = (\bar{P} - c)[1 - F(k_{sr} + T)] \tag{72}$$

$$\pi_{cp} = (\bar{P} - c)[1 - F(k_{cp} - T)] \tag{73}$$

As before, r is the capacity cost in both markets. m is the capacity payment in market CP. Assume for the moment that CP (the only exporter when demand and SoS is symmetric), owns the transmission rights. This assumption with be relaxed later.

Market SR

Recall that capacity in market SR can be either market based (k_{sr}^c) or reserved (k_{sr}^{cSR}) where subscript c denotes we are examining the paradigm where capacity is sometimes binding.

Each market allows entry: the zero-profit condition pins down the installed capacities:

$$\pi_{sr} = 0 = (\bar{P} - c)[1 - F(k_{sr}^c + T)] - r \Rightarrow k_{sr}^c = F^{-1}(1 - \frac{r}{\bar{P} - c}) - T \tag{74}$$

Note that $k_{sr}^c = F^{-1}(1 - \frac{r}{\bar{P} - c}) - T = k_{sr}^i - T > k_{sr}^i - \frac{k^T - k_{sr}}{2} = k_{sr}^i - k^T + \frac{k^T + k_{sr}}{2} > 2k_{sr}^i - k^T$. Hence $k_{sr} < k_{sr}^c < k_{sr}^i$

Strategic reserves are used during scarcity. The expected revenues are

$$\mathbb{E}[SR] = (\bar{P} - c)\left(\int_{k_{sr}+T}^{k_{cp}-T} (l_{sr} - (k_{sr} + T))f(l_{sr})dl_{sr} + \int_{k_{cp}-T}^{k_{cp}} (2l_{sr} - (k_{sr} + k^T))f(l_{sr})dl_{sr} + (1 - F(k^T))(k^T - k_{sr})\right)$$

Revenues of the strategic reserves need to be subtracted from the costs to consumers. The cost of support for capacity (SR) is therefore

$$CP^c = r * (k^T - k_{sr}) - \mathbb{E}[SR]$$

Expected payments by consumers on the energy market are:

$$CM_{sr}^c = c \int_0^{k_{sr}+T} l_{sr} f(l_{sr})dl_{sr} + \bar{P}\left(\int_{k_{sr}+T}^{k^T} l_{sr} f(l_{sr})dl_{sr} + (1 - F(k^T))k^T\right)$$

Total costs for the consumers are :

$$C_{sr}^c = CM_{sr}^c + CP_{sr}^c = c\int_0^{k_{sr}+T} l_{sr}f(l_{sr})dl_{sr} + c\left(\int_{k_{sr}+T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + (1-F(k^T))k^T\right) \tag{75}$$

$$+ (\bar{P}-c)\left(\int_{k_{sr}+T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + (1-F(k^T))k^T\right) + rk^T - rk_{sr} \tag{76}$$

$$-(\bar{P}-c)\left(\int_{k_{sr}+T}^{k_{cp}-T}(l_{sr}-(k_{sr}+T))f(l_{sr})dl_{sr} + \int_{k_{cp}-T}^{k_{cp}}(2l_{sr}-(k_{sr}+k^T))f(l_{sr})dl_{sr} + (1-F(k^T))(k^T-k_{sr})\right) \tag{77}$$

$$= C_{sr,cp}^i - (\bar{P}-c)k_{sr}[F(k_{cp}) - F(k_{sr}+T)] \tag{78}$$

$$+ (\bar{P}-c)\left(\int_{k_{sr}+T}^{k_{cp}-T}(k_{sr}+T)f(l_{sr})dl_{sr} - \int_{k_{cp}-T}^{k_{cp}}(l_{sr}-(k_{sr}+k^T))f(l_{sr})dl_{sr}\right) \tag{79}$$

$$= C_{sr,cp}^i + (\bar{P}-c)\Big((k_{sr}+T)(F(k_{cp}-T) - F(k_{sr}+T)) + k_{sr}(F(k_{sr}+T) - F(k_{cp})) \tag{80}$$

$$- \int_{k_{cp}-T}^{k_{cp}}(l_{sr}-(k_{sr}+k^T))f(l_{sr})dl_{sr}\Big) \tag{81}$$

$$= C_{sr,cp}^i + (\bar{P}-c)\left(\int_{k_{cp}-T}^{k_{cp}}(k^T - l_{sr})f(l_{sr})dl_{sr} + T(F(k_{cp}-T) - F(k_{sr}+T))\right) \tag{82}$$

$$> C_{sr,cp}^i \tag{83}$$

Market CP

Similarly, we must have

$$rk_{cp} = m^c k_{cp} + \Pi_{cp} = mk_{cp} + (\bar{P}-c)\left[(1-F(k_{cp}-T))\,k_{cp} + (F(k_{cp}-T) - F(k_{sr}+T))T\right] \tag{84}$$

$$\Rightarrow m^c = r - (\bar{P}-c)[1 - F(k_{cp}-T) + (F(k_{sr}+T) - F(k_{cp}-T))T/k_{cp}] \tag{85}$$

Note that the capacity payment per unit is smaller than in the isolated case, but higher than if transmission capacity is infinite:

$$m^c = m^i - (\bar{P}-c)\left[(F(k_{cp}) - F(k_{cp}-T)) + (F(k_{cp}-T) - F(k_{sr}+T))T/k^T\right] < m^i \tag{86}$$

$$m^c = m^i - (\bar{P}-c)\left[(F(\frac{k_{cp}+k_{sr}}{2}) - F(k_{cp}-T)) + (F(k_{cp}-T) - F(k_{sr}+T))T/k^T\right] > 0 \tag{87}$$

The cost of the support for capacity (CP) is therefore

$$CP_{cp}^c = mk_{cp}$$

Expected payments on the energy markets are:

$$CM_{cp}^c = c\int_0^{k_{cp}-T} l_{sr}f(l_{sr})dl_{sr} + \bar{P}\left(\int_{k_{cp}-T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + (1-F(k^T))k^T\right)$$

Thus we have total costs:

$$C_{cp}^c = CM_{cp}^c + CP_{cp}^c = c\int_0^{k_{cp}-T} l_{sr}f(l_{sr})dl_{sr} + c\int_{k_{cp}-T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + c(1-F(k^T))k^T \quad (88)$$

$$+ (\bar{P}-c)\left(\int_{k_{cp}-T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + (1-F(k^T))k^T\right) \quad (89)$$

$$+ rk_{cp} - (\bar{P}-c)[(1-F(k_{cp}-T))k_{cp} + (F(k_{cp}-T)-F(k_{sr}+T))T] \quad (90)$$

$$= C_{sr,cp}^i - (\bar{P}-c)\left[(F(k_{cp})-F(k_{cp}-T))k_{cp} - \int_{k_{cp}-T}^{k^T} l_{sr}f(l_{sr})dl_{sr} + T(F(k_{cp}-T)-F(k_{sr}+T))\right] \quad (91)$$

$$= C_{sr,cp}^i - (\bar{P}-c)\left[\int_{k_{cp}-T}^{k^T}(k^T-l_{sr})f(l_{sr})dl_{sr} + T(F(k_{cp}-T)-F(k_{sr}+T))\right] \quad (92)$$

$$> C_{cp} \text{ and } < C_{sr,cp}^i \quad (93)$$

Unlike when the line is uncongested, CP's firms can enjoy a congestion rent –which didn't exist before.

Overall welfare

Again, and for the same reasons as in the previous subsection, SR's extra costs, and CP's cost reduction cancel out. The costs changes are less than in the previous case (unlimited capacity) as congestion limits flows.

If market SR were to stick to a strategic reserve paradigm, it would be better off with little transmission capacity.

Transmission rights

Here we implicitly assumed that market CP (the exporter) owned the transmission rights and therefore benefited from the congestion rent. If we relax this hypothesis, considering that SR owns a share α of the transmission capacity (and CP owns the remainder $1-\alpha$), the consumer costs are modified as follows:

$$C^c_{sr} = C^i_{sr,cp} + (\bar{P} - c)\left[\overbrace{\int_{k_{cp}-T}^{k_{cp}} (k^T - l_{sr}) f(l_{sr}) dl_{sr}}^{B's\ undercutting} + (1-\alpha)\overbrace{T(F(k_{cp} - T) - F(k_{sr} + T))}^{congestion\ rent}\right] \quad (94)$$

$$C^c_{cp} = C^i_{sr,cp} - (\bar{P} - c)\left[\int_{k_{cp}-T}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr} + (1-\alpha) T(F(k_{cp} - T) - F(k_{sr} + T))\right] \quad (95)$$

In particular, if SR owns all transmission rights, its extra costs of reliability are smaller than when transmission was infinite – SR is protected by limited import capacity from CP, and gets the congestion rents. However, market SR is still over-paying CP firms, when CP exports to SR at high prices, and transmission is not yet congested. Overall welfare remains unchanged.

The conclusions of this subsection can be summarized in the following proposition:

Proposition 6 *When transmission is binding, a market with a capacity payment will decrease its SoS costs, through a partial transfer of the burden to its strategic reserve neighbour, even if the country with a strategic reserve owns the transmission rights.*

C Interconnected SR/CP markets –general case

We denote by exponent "*eq*" variables in the case of interconnected markets with asymmetric demand, at equilibrium (without TSOs' intervention). The results found in the previous section carry over. As in section 6, Define $l = (l_{sr}, l_{cp})$. Denote by $f(l_{sr}, l_{cp})$ the joint distribution of l. The cumulative distribution of total demand is denoted $F_l(l)$).

Transmission is never binding

Again, if transmission is not binding, free entry yields: $1 - F_l(k^T_{cp} + k_{sr}) = \frac{r}{\bar{P}-c} = 1 - F_l(k^{eq}_{sr} + k^{eq}_{cp})$. Therefore, again, we have that operational capacity in SR acts as a buffer, such that total capacity remains optimal: $k_{sr} = k^{eq}_{sr} + k^{eq}_{cp} - k^T_{cp} = K^{eq} - k^T_{cp}$. Again, if SR wants to maintain is SoS level, it will have to compensate for the decrease in local operational capacity. Assume that markets SR and CP want to increase their SoS, with would translate into the construction of Δ_{sr} and Δ_{cp} strategic reserve. Define $\Delta_{sr} + \Delta_{cp} = 2\Delta$. Assume that transmission is never binding and that market SR uses its strategic reserve to serve demand in market CP, when the latter is tight. First, observe that if both countries have the same capacities (either supported with a CP or complemented with SR), they will enjoy the same SoS. Indeed, if both countries use a SR, then a simple argument of symmetry shows both countries enjoy the same demand coverage. Assume now market CP implements a capacity payment. It will provide support until its capacity allows demand coverage to reach a given value. Then, if market SR adjusts its capacity such that $k_{cp} = k_{sr}^T = k_{sr}^{eq} + \Delta_{sr}$, demand coverage in SR remains identical as total demand coverage is maintained and CP's demand coverage is maintained. Therefore if two integrated countries have the same SoS target ($\Delta_{sr} = \Delta_{cp}$), they will have the same capacity target.

If both countries implement a SR of same size, symmetry means there are some cross border rent extractions, but those cancel out:

$$RE(k_{a=SR}^T, k_{b=SR}^T) = 0 \tag{96}$$

Let us first calculate the rent extraction from market SR (capacity k_{sr}) towards market CP (capacity $k_{cp} = k_{cp}^T$), with $k_{sr} + k_{cp}^T = k_{sr}^{eq} + k_{cp}^{eq} = K^{eq}$

$$\frac{RE(k_{a=SR}^T, k_{b=CP}^T)}{\bar{P} - c} = \iint_{\substack{K^{eq} + 2\Delta \le l_{sr} + l_{cp} \\ k_{cp}^T > l_{cp}}} (k_{cp}^T - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} - \iint_{\substack{K^{eq} + 2\Delta \le l_{sr} + l_{cp} \\ k_{sr}^T > l_{sr}}} (k_{sr}^T - l_{sr}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{97}$$

$$+ \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} > l_{cp}}} (k_{cp} - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{98}$$

$$- \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} < l_{cp}}} (l_{cp} - k_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{99}$$

Assuming demands are i.i.d. distributed: by symmetry, the first two terms cancel out:

$$\tag{100}$$

$$= \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} > l_{cp}\ ,\ k_{sr}^T > l_{sr}}} (k_{cp} - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{101}$$

$$+ \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} > l_{cp}\ ,\ k_{sr}^T < l_{sr}}} (k_{cp} - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{102}$$

$$- \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} < l_{cp}}} (l_{cp} - k_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{103}$$

$$= \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} > l_{cp}\ ,\ k_{sr}^T > l_{sr}}} (k_{cp} - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{104}$$

$$+ \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} > l_{cp}\ ,\ k_{sr}^T < l_{sr}}} (k_{cp} - l_{cp} + k_{sr}^T - l_{sr}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{105}$$

$$+ \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{sr}^T < l_{sr}}} (l_{sr} - k_{sr}^T) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{106}$$

$$- \iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{cp} < l_{cp}}} (l_{cp} - k_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{107}$$

By symmetry, the last two terms cancel out:

$$= \overbrace{\iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \\ k_{sr}^T > l_{sr}\ l_{cp} < k_{cp}}} (k^{eq} + \Delta - l_{cp}) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp}}^{B\ undercuts\ SR's\ reserve\ capacity} \tag{108}$$

$$+ \overbrace{\iint_{\substack{K^{eq} \le l_{sr} + l_{cp} \le K^{eq} + 2\Delta \\ k_{sr}^T < l_{sr}}} (K^{eq} + 2\Delta - (l_{sr} + l_{cp})) f(l_{sr}, l_{cp}) dl_{sr} dl_{cp}}^{net\ benefit\ from\ selling\ into\ a\ tight\ neighbouring\ market} \tag{109}$$

$$> 0 \tag{110}$$

Therefore, there are some cross-border profits, in favour of the market with a capacity payment.

Let us check who bears the cost of SoS. To get the overall welfare cost we just need to compare the system costs for a market in a EO/EO setting, with a market in a SR/SR setting where each market funds Δ strategic reserve capacity. The incremental total welfare cost $-\Delta W_{sr+cp}$, normalized by the instantaneous scarcity rent $\bar{P} - c$ is:

$$\frac{-\Delta W_{sr+cp}}{\bar{P}-c} = \overbrace{2 * \Delta r}^{capacity\ costs} - \overbrace{(\bar{P}-c)\left(\mathcal{L}_{cp}(k^*+\Delta_{sr}, k^*+\Delta_{cp}) - \mathcal{L}_{eo}(k^*, k^*) + \mathcal{L}_{sr}(k^*+\Delta_{sr}, k^*+\Delta_{cp}) - \mathcal{L}_{eo}(k^*, k^*)\right)}^{welfare\ increase} \tag{111}$$

$$= (\bar{P}-c)\left(2\Delta(1-F(K^{eq}) - 2\Delta(1-F(K^{eq}+2\Delta)) - \iint_{\substack{K^{eq} < l_{sr}+l_{cp} \\ l_{cp} < k^{eq} - T}} l_{sr} + l_{cp} - K^{eq} f(l_{sr}, l_{cp}) dl_{sr} dl_{cp}\right) \tag{112}$$

$$= (\bar{P}-c)\iint_{K^{eq} < l_{sr}+l_{cp} < K^{eq}+2\Delta} (K^{eq} + 2\Delta - (l_{sr}+l_{cp}))\, f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} \tag{113}$$

We've seen that if markets are perfectly integrated, consumers pay the same price in the energy market CP and EO. We found that $m = 0$: the capacity support costs nothing to CP consumers. That is, only SR consumers are paying for the additional capacity. Thus, they pay for both CP and SR's SoS.

SR needs to fund 2Δ capacity. The cost of support in SR is:

$$\frac{-\Delta SR_{cp}}{\bar{P}-c} = \overbrace{2 * \Delta(1-F(K^{eq}))}^{SR\ capacity\ costs} \tag{114}$$

$$- \overbrace{(\bar{P}-c)\left(2\Delta \iint_{K^{eq}+2\Delta < l_{sr}+l_{cp}} f(l_{sr}, l_{cp}) dl_{sr} dl_{cp} + \iint_{K^{eq} < l_{sr}+l_{cp} < K^{eq}+2\Delta} (l_{sr}+l_{cp}-K^{eq}))\, f(l_{sr}, l_{cp}) dl_{sr} dl_{cp}\right)}^{welfare\ increment} \tag{115}$$

$$= \frac{-\Delta W_{sr+cp}}{\bar{P}-c} \tag{116}$$

That is, market CP gets all its SoS financed by SR consumers: again we observe that all the welfare costs of implementation of a SoS standard with a CP strategy has been transferred to the SR neighbour. CP increases its SoS, and maintains its welfare level at the expense of market SR. Note that $\Delta SR_{cp} = 2RE(k^T_{a=SR}, k^T_{b=CP})$. This means the whole cost of SoS is borne by the consumers in the market with a strategic reserve, due to CP's cross-border rent extraction. The rationale is fairly intuitive; by giving a slight competitive advantage to its operational capacity, CP attracts investors. SR compensates the loss by increasing its strategic reserve. From CP's point of view, when it comes to SoS, SR's *operational* capacity and SR's *reserve* capacity are perfect substitutes. Therefore discouraging investment in operational capacity in SR does not harm SR's contribution to CP's SoS.

Transmission is binding

So far we have assumed that transmission was greater than maximum demand, such that there is no congestion. This situation is highly unlikely. Congestion will have the virtue to limit the spillover effect of the dis-harmonized market designs, but also to make part of the transfers appropriable by the prejudiced market, even if it is not the exporter.

As before, two countries with the same SoS target will have the same capacity target, whatever the market design is. In addition to this, demand coverage will be the same in both countries. This means that the capacity and operation costs will be same in both markets. The only difference will be the rent transfers. Denote α_e (α_i) the share of the congestion rent SR gets on exports(on imports). CP gets the remaining $1-\alpha_e$ $(1-\alpha_i)$. Rent extraction from SR towards CP is:

$$\frac{RE(k^T_{a=SR}, k^T_{b=CP}, T, \alpha)}{\bar{P}-c} = \tag{117}$$

$$T\left(\overbrace{(1-2\alpha_i)\iint_{\substack{l_{cp}<k^T-T\\ l_{sr}>k^T+T}} f(l_{sr},l_{cp})dl_{sr}dl_{cp}}^{rent\ extraction\ differential\ from\ exports\ to\ SR} + \overbrace{(1-2\alpha_e)\iint_{\substack{k^T+T<l_{cp}\\ l_{sr}<k_{sr}-T}} f(l_{sr},l_{cp})dl_{sr}dl_{cp}}^{A\ gets\ \alpha_e\ of\ the\ congestion\ generated\ by\ CP's\ demand}\right) \tag{118}$$

$$+\iint_{\substack{K^{eq}<l_{sr}+l_{cp}\\ k^T-T<l_{cp}<k^T}} (k^T-l_{cp})f(l_{sr},l_{cp})dl_{sr}dl_{cp} - \iint_{\substack{K^{eq}<l_{sr}+l_{cp}\\ k^T-T<l_{sr}<k^T}} (k^T-l_{sr})f(l_{sr},l_{cp})dl_{sr}dl_{cp} \tag{119}$$

$$-\iint_{\substack{K^{eq}<l_{sr}+l_{cp}\leq 2k^T\\ k^T<l_{cp}<k^T+T}} (l_{cp}-k^T)f(l_{sr},l_{cp})dl_{sr}dl_{cp} - T\iint_{\substack{k_{sr}-T<l_{sr}\leq k^T-T\\ k^T+T\leq l_{cp}}} (l_{cp}-k^T)f(l_{sr},l_{cp})dl_{sr}dl_{cp} \tag{120}$$

A wise allocation of the transmission rights may allow to correct for the unwanted monetary tranfers from SR to CP. If demand is uniform and the exporters get the whole congestion rent ($\alpha_e = 1$, $\alpha_i = 0$) the rent extraction remains positive (i.e. in favour of CP). That means SR must not only appropriate all the rent generated by its exports, but also some of those generated by its imports. Whether one can actually make sure overall transfers cancel out depends on the sign of $RE(k^T_{a=SR}, k^T_{b=CP}, T, \alpha = (1,1))$. One can easily see that when T is "large", we are back to the previous case, and RE is always positive (i.e. SR is prejudiced). Conversely, when $T \to 0$, $RE(k^T_{a=SR}, k^T_{b=CP}, T, \alpha = (1,1))$ is positive (the only positive term is quadratic in T while the two first terms are of first order): that is, there exists a maximum transmission capacity T^* such that transfers can just be neutralized if SR owns enough transmission rights. If $T > T^*$, SR will be prejudiced, even if it appropriates all congestion rents. Note that when the congestion rent is shared equally between the two markets ($\alpha_e = \alpha_i = 0.5$), demand is i.i.d following a uniform distribution, and $T < Min[k^T, \bar{l} - k^T]$, SR is no longer prejudiced.

D Interconneted EO/SR markets – symmetric markets

When SR (strategic reserve) is connected with EO (no remuneration scheme), a notable point is that SR's strategic reserve does not affect prices, as those are activated only when the price hits the cap. Thus, the investment signal in SR and EO is unchanged, compared to the isolated cases.

Note that in contrast with the previous case (SR vs CP), total welfare will be improved compared to the isolated case, even if demands are perfectly correlated. This is due to the fact the reserved capacity in SR, will have an increased utilization –thereby alleviating the capacity support costs in markets SR – and at the same time will provide an improved demand coverage in market EO. In short, improved use of existing capacity (higher utilization rate) means total welfare increases. EO's SoS is improved (even if EO is indifferent to its SoS level), while SR's SoS is unchanged, and its costs decrease.

As before, we start by assuming that transmission is never binding (i.e. $T > \frac{k^T - k^i_{sr}}{2}$).

Transmission is never binding

Note that given that the price signal is not distorted by the strategic reserve (as it operates only when price is at cap), the operational capacity is the same in each market: $k_{eo} = k^i_{eo} = k^i_{sr} = k^*$. With $l_{sr} = l_{eo}$, transmission flows will only occur from SR to EO.

Market SR

The total cost for consumer SR equal the costs in the isolated case, minus some high priced exports when EO is tight while SR is not tight yet (based on total capacity):

$$C_{sr} = C^i_{sr,cp} - (\bar{P} - c)\left(\overbrace{\int_{k^i_{sr}}^{\frac{k^i_{sr}+k^T}{2}} (l_{sr} - k^i_{sr}) f(l_{sr}) dl_{sr}}^{EO\ is\ tight,\ overall\ system\ is\ not} + \underbrace{\int_{\frac{k^i_{sr}+k^T}{2}}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr}}_{EO\ is\ tight,\ SR\ is\ not,\ overall\ system\ is} \right) \tag{121}$$

Market EO

Since $l_{eo} = l_{sr}$, any imports will be high-priced [14]. If $\bar{P} = VoLL$, society EO is indifferent between paying $\bar{P}$ for some imports and curtailing some of its consumers: Welfare in EO remains unchanged by the interconnection, and $k_{eo} = k^* = k^i_{sr}$. We have an increase in costs, exactly offset by an equivalent

[14] If $l_{sr} \leq k_{eo}$ both markets are loose and $P_{sr} = P_{eo} = c$, $t = 0$. If $l_{sr} > k^T$, both markets are tight and curtail: $P_{sr} = P_{eo} = \bar{P}$, $t = 0$. If $k_{eo} < l_{sr} \leq k^T$ market EO is tight, and SR's operational capacity does not suffice to cover SR's demand. SR's reserve capacity is activated. We have $P_{sr} = P_{eo} = \bar{P}$ and positive transmission flows

increase in gross surplus:

$$C_{eo} = C_{eo}^i + (\bar{P} - c)\left(\int_{k_{sr}^i}^{\frac{k_{sr}^i + k^T}{2}} (l_{sr} - k_{sr}^i) f(l_{sr}) dl_{sr} + \int_{\frac{k_{sr}^i + k^T}{2}}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr}\right) \tag{122}$$

The expected curtailment was $\mathcal{L}^* = \int_{k^*}^1 (l_{eo} - k^*) f(l_{eo}) dl_{eo}$. After interconnection it becomes:

$$\mathcal{L}_{eo} = \int_{\frac{k^* + k^T}{2}}^{k^T} (2l_{eo} - 2k^*) f(l_{eo}) dl_{eo} + \int_{k^T}^1 (l_{eo} - k_{eo}) f(l_{eo}) dl_{eo} \tag{123}$$

$$= \mathcal{L}^* - \int_{k^*}^{\frac{k^* + k^T}{2}} (l_{eo} - k^*) f(l_{eo}) dl_{eo} - \int_{\frac{k^* + k^T}{2}}^{k^T} (k^T - l_{eo}) f(l_{eo}) dl_{eo} < \mathcal{L}^* \tag{124}$$

Welfare

Given that the strategic reserve is dispatched in priority in the local market, SR's demand coverage (and SoS) remains unchanged after interconnecting with EO. The cost reduction equals the welfare increment in SR. Since price cap equals the VoLL, EO is indifferent to being connected with SR or not. There is therefore an overall welfare increase, driven by SR's cost reduction.

In addition to this, EO enjoys an increment in demand coverage of:

$$\left(\int_{k_{sr}^i}^{\frac{k_{sr}^i + k^T}{2}} (l_{sr} - k_{sr}^i) f(l_{sr}) dl_{sr} + \int_{\frac{k_{sr}^i + k^T}{2}}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr}\right) > 0$$

Therefore, we have the following proposition:

Proposition 7 *When a market with a strategic reserve has an energy-only neighbour, interconnection is mutually beneficial –for SR in terms of cost reduction, for EO in terms of additional demand coverage.*

Transmission is binding

Note that when demands are equal, there will be no congestion rents: $l_{sr} = l_{eo} < k_{sr} = k_{eo} \Rightarrow P_{sr} = P_{eo} = c$ and $l_{sr} = l_{eo} > k_{sr} = k_{eo} \Rightarrow P_{sr} = P_{eo} = \bar{P}$

Market SR

The total cost for consumer SR equal the costs in the isolated case, minus some high priced exports when EO is tight while SR is not tight yet (based on total capacity):

$$C_{sr} = C^i_{sr,cp} - (\bar{P} - c)\left(\int_{k^i_{sr}}^{k^i_{sr}+T} (l_{sr} - k_{sr}) f(l_{sr}) dl_{sr} + T(F(k^T - T) - F(k^i_{sr} + T)) + \int_{k^T - T}^{k^T} (k^T - l_{sr}) f(l_{sr}) dl_{sr}\right) \tag{125}$$

Market EO

If $\bar{P} = VoLL$, society EO is indifferent between paying $\bar{P}$ for some imports and curtailing some of its consumers: Welfare in EO remains unchanged by the interconnection.

Welfare

The increment in total welfare stems from a better use of the strategic reserve, part of which sometimes exports to EO at high prices: EO's consumers are (weakly) better off[15], and the amounts they pay for this peak energy alleviates SR's support scheme.

Note here that strategic reserve has the characteristics of a public good ((non-excludable, non rivalrous if the owner doesn't need it). EO will benefit from SR's strategic reserve. Thus, there can be a war of attrition with both countries waiting for the other to implement a strategic reserve, and then enjoy it. When a market has a greater SoS standard, and it is public knowledge, a standard economic result is that it will lose the war of attrition with probability 1, and thus the war does not happen. The market that's most averse to curtailment will implement its strategic reserve first. The case with unknown or private information, has been extensively covered in the economic literature (see [Tirole, 1988]) and goes beyond the scope of this paper.

E Interconnected EO/SR markets –general case

Again, if transmission is not binding, free entry yields: $1 - F_l(k^T_{cp} + k_{sr}) = \frac{r}{\bar{P}-c} = 1 - F_l(K^{eq})$. A strategic reserve does not modify the price signal: $k_{sr} = (1-\alpha)K^{eq}$ and $k_{eo} = \alpha K^{eq}$. SR increases its SoS through a strategic reserve. As in the correlated demand case, EO will enjoy increased SoS, at no welfare cost. High-priced exports to EO will alleviate the burden to SR's consumers.

[15] Again, EO gets additional demand coverage, at no welfare cost

Assume that market SR uses its strategic reserve to serve demand in market EO, when the latter is tight.

Welfare in EO, compared to the EO/EO case is unchanged as operational capacities in both markets are unchanged, and all imports from the neighbouring strategic reserve come at a price equal to VoLL.

The EENS in SR is decreased, down to SR's target:

$$\mathcal{L}_{sr}^T = \mathcal{L}_{eo}(k_{sr}, < k_{eo}) - \iint_{\substack{k_{sr} \leq l_{sr} \leq k_{sr}^T \\ k_{eo} \leq l_{eo}}} (l_{sr} - k_{sr}) f(l) dl - \iint_{\substack{k_{eo} - T \leq l_{eo} \leq k_{eo} \\ 2k_{sr} \leq l_{eo} + l_{sr} \leq k_{sr} + k_{sr}^T}} (l_{sr} + l_{eo} - 2k_{sr}) f(l) dl \tag{126}$$

$$- \iint_{\substack{k_{sr} + T \leq l_{sr} \leq k_{sr}^T + T \\ l_{eo} \leq k_{eo} - T}} (l_{sr} + l_{eo} - 2k_{sr}) f(l) dl \tag{127}$$

$$- (k_{sr}^T - k_{sr}) \left(\iint_{\substack{k_{sr}^T \leq l_{sr} \\ l_{eo} \geq k_{eo} - T \\ l_{eo} + l_{sr} > k_{sr} + k_{sr}^T}} f(l) dl + \iint_{\substack{k_{sr}^T + T \leq l_{sr} \\ l_{eo} \leq k_{eo} - T}} f(l) dl \right) \tag{128}$$

This EENS target will pin k_{sr}^T down. EO will enjoy increased SoS as well:

$$\mathcal{L}_{eo}(k^T, k_{eo}) = \mathcal{L}_{eo}(k_{sr}, k_{eo}) - \iint_{\substack{k_{sr} - T \leq l_{sr} \leq k_{sr} \\ 2k_{sr} \leq l_{sr} + l_{eo}}} Min[T, k_{sr} - l_{sr}] l_{sr} - k_{sr}) f(l) dl \tag{129}$$

$$- \iint_{\substack{k_{eo} \leq l_{eo} \leq k_{eo} + T \\ l_{eo} + l_{sr} \leq k_{sr} + k_{sr}^T \\ k_{sr} \leq l_{sr}}} (l_{eo} - k_{eo}) f(l) dl \tag{130}$$

$$- T \iint_{\substack{k_{sr} \leq l_{sr} \leq k_{sr} + T \\ k_{eo} + T \leq l_{eo}}} f(l) dl + \iint_{\substack{k^T - T \leq l_{sr} \leq k^T \\ 2k_{sr} \leq l_{eo} + l_{sr}}} (k^T - l_{sr}) f(l) dl \tag{131}$$

The welfare cost of the strategic reserve is:

$$\frac{\Delta W(k^T, k_{eo})}{\bar{P} - c} = r k_{sr}^T \tag{132}$$

$$- \left(\underbrace{\mathcal{L}_{sr}(k^T, k_{eo}) - \mathcal{L}_{eo}(k_{sr}, k_{eo})}_{energy\ served\ locally\ by\ the\ strategic\ reserve} + \underbrace{\mathcal{L}_{eo}(k^T, k_{eo}) - \mathcal{L}_{eo}(k_{sr}, k_{eo})}_{energy\ served\ abroad\ by\ the\ strategic\ reserve} \right) \tag{133}$$

That is, the welfare cost of the strategic reserve is alleviated by both demand coverage at home and, as a by-product, by sales made abroad.

We see that overall welfare is increased compared to a situation where exports from SR's strategic reserve would be forbidden. Welfare in EO is unchanged, and SR gets additional cross-border sales revenues. The fundamental reason for this increase in welfare is that the utilization rate of the strategic reserve has increased.

F Social cost of SoS

Comparing welfare in an Energy-only market with welfare in a market with a CRM, we can compute the social costs of security of supply. The welfare cost[16] of SoS is: $\Delta W^i(k^T) = (\bar{P}-c)\left(\int_{k^*}^{k^T}(k^T-l)f(l)dl\right)$. Figure 11 shows that not only the total cost, but also the marginal total cost of support for capacity is increasing in the capacity target. The rationale is that when total capacity is just above the market equilibrium, the last added unit is still almost profitable: only a small amount of subsidy is required. Conversely when total capacity is large, the last unit is unlikely to be much used in the market (and therefore, unlikely to have any social value): the cost to consumers approaches r when $k^T \to \infty$.

Proposition 8 *When markets are isolated, the cost of an increase in SoS is the same, whether the local regulator implements a strategic reserve or a form of capacity payment. The social cost of a marginal capacity addition is close to zero for the first added units, and monotonically increases to r when total capacity approaches maximum demand*

Proof.

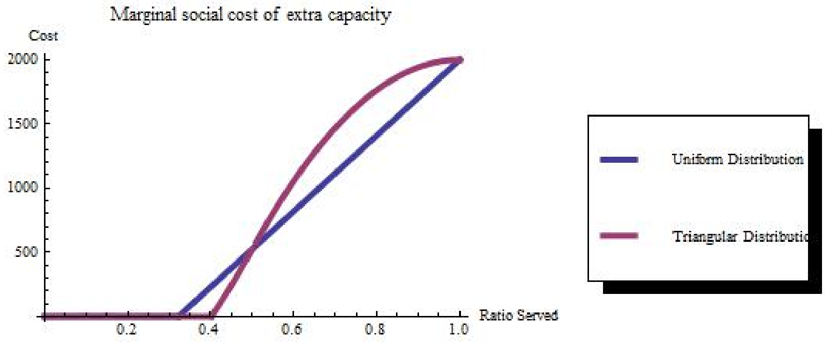
Marginal social cost of an additional unit of reserve capacity:

$$-\frac{\partial W^i_{sr}}{\partial k^T} = r - (\bar{P}-c)\left[1-F(k^T)\right] = (\bar{P}-c)\left[F(k^T)-F(k^*)\right] > 0$$

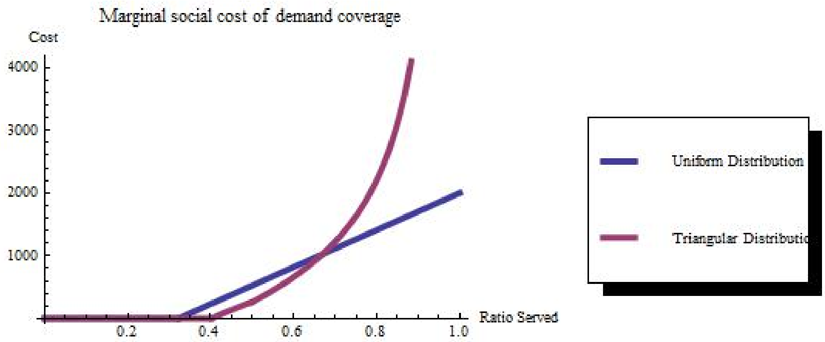
Marginal social cost of an additional unit of demand coverage:

$$-\frac{\frac{\partial W^i_{sr}}{\partial k^T}}{\frac{\partial F(k^T)}{\partial k^T}} = \frac{r}{f(k^T)} - (\bar{P}-c)\frac{1-F(k^T)}{f(k^T)} = (\bar{P}-c)\frac{F(k^T)-F(k^*)}{f(k^T)} > 0$$

[16] note that this cost does depend on r, as k^* is a function of r



(a)



(b)

Figure 11: Marginal social cost of extra capacity (top) and Marginal social cost of demand coverage(bottom), when demand follows a uniform distribution (blue) or triangular demand distributions over $[0, 1]$ (purple).
$r = 2000$,$\bar{P} = 3000$,$c = 50$

■

G No control on exports

We've assumed so far that TSOs were controlling exports. That is, if its system it tight, it can curtail exports to avoid curtailments or brownouts. In this simple setting however, and under the European Commission Security of Supply directive, a TSO might not be allowed to control exports –even though current national network codes allow it, in direct contradiction with the security of supply directive (see [Mastropietro et al., 2015] for an exposition of this problem).

Luckily for our analysis, in real life in case of a tight situation, the electricity produced is likely to be sold locally. Indeed, cross-border transaction fees or transmission losses mean local consumption will always be preferred by operators, meaning export reduction will happen, even absent TSO intervention.

Assume there are some small cross-border transaction cost ν such that the importer receives only a share $(1 - \nu)$ of the price paid. One can think of ν as an administrative cost. A similar way to think of it would be to consider that there are some transmission losses.

Free entry conditions are:

$$r = \left(\frac{c}{1-\nu} - c\right) \iint_{\substack{k_{eo} < l_{eo} \leq k_{eo} + T \\ l_{cp} + l_{eo} \leq K^{eq}}} f(l)dl + \left(\bar{P}(1-\nu) - c\right) \iint_{\substack{k_{eo} - T < l_{eo} \leq k_{eo} \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \tag{134}$$

$$+ (\bar{P} - c) \left(\iint_{\substack{k_{eo} + T < l_{eo} \\ l_{cp} \leq k_{cp} - T}} f(l)dl + \iint_{\substack{l_{eo} \geq k_{eo}, l_{cp} \geq k_{cp} - T \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \right) \tag{135}$$

$$r = \left(\frac{c}{1-\nu} - c\right) \iint_{\substack{k_{cp} < l_{cp} \leq k_{cp} + T \\ l_{cp} + l_{eo} \leq K^{eq}}} f(l)dl + \left(\bar{P}(1-\nu) - c\right) \iint_{\substack{k_{cp} - T < l_{cp} \leq k_{cp} \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \tag{136}$$

$$+ (\bar{P} - c) \left(\iint_{\substack{k_{cp} + T < l_{cp} \\ l_{eo} \leq k_{eo} - T}} f(l)dl + \iint_{\substack{l_{cp} \geq k_{cp}, l_{eo} \geq k_{eo} - T \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \right) + m \tag{137}$$

Hence, the capacity payment is:

$$m = c\frac{\nu}{1-\nu} \left(\iint_{\substack{k_{eo} < l_{eo} \leq k_{eo} + T \\ l_{cp} + l_{eo} \leq K^{eq}}} f(l)dl - \iint_{\substack{k_{cp} < l_{cp} \leq k_{cp} + T \\ l_{cp} + l_{eo} \leq K^{eq}}} f(l)dl \right) \tag{138}$$

$$+ \nu\bar{P} \left(\iint_{\substack{k_{cp} - T < l_{cp} \leq k_{cp} \\ l_{cp} + l_{eo} \leq K^{eq}}} f(l)dl - \iint_{\substack{k_{eo} - T < l_{eo} \leq k_{eo} \\ l_{cp} + l_{eo} \geq K^{eq}}} f(l)dl \right) \tag{139}$$

$$+ (\bar{P} - c) \left(\iint_{\substack{k_{eo} + T < l_{eo} \\ l_{cp} \leq k_{cp} - T}} f(l)dl - \iint_{\substack{k_{cp} + T < l_{cp} \\ l_{eo} \leq k_{eo} - T}} f(l)dl \right) \tag{140}$$

The first term is the compensation for the difference in profit made when there are some low-price exports. This term will be positive as CP is likely to export more often than EO, increasing the local prices from c to $\frac{c}{1-\nu}$ (low priced exports benefit only the importer's consumers). The second term compensates for the difference in profit when there are some high-price exports. This term will be positive too, as CP is more likely to export to EO due to its CRM-promoted capacity. Doing so, EO's welfare is unchanged, while CP's profits increase by only $\bar{P}(1-\nu) - c$ (compared to $\bar{P} - c$ in the no-transaction-costs paradigm) . The third term corresponds to the states of the world where EO's prices are high thanks to the interconnection being congested, minus the situations where CP's prices are high for the same reason. It will also be positive, as long as transmission capacity is sometimes congested.

Note that if $\nu = 0$ and transmission is large, we find again that $m = 0$. Interestingly, when there are some transaction costs (or similarly, transmission losses), capacity payment must increase. Indeed, capacity in CP is no longer a perfect substitute to capacity inEO. CP's plants willing to sell in

EO's market are at a competitive disadvantage to EO's in EO's market and therefore, an additional payment to producers is required in order to for CP to meet its target.

Abstracting from this small capacity payment by CP to compensate for the transaction cost, the results will be exactly similar to those of the previous subsection. Relaxing the "national preference" results, and introducing transmission losses takes us back to the "national preference" paradigm.

Thus, we've shown that electricity will preferably be sold to local consumers first. However, it might very well be the case that electricity flows go in the wrong direction, due to the law of physics: if the situation is worse (i.e. magnitude of curtailment is greater) on the EO market, electricity may flow from CP to EO, even though prices are the same. This does not undermine our analysis: if power flows to EO instead of staying in CP in some states of the world, CP will simply increase its capacity target until it reaches it required SoS. EO's operational capacity will decrease further so that total capacity remains optimal, and the very same phenomenon as before occurs. The case when the spillovers are so large that CP cannot meet its target at all is discussed in section 8.1.

H Cross-border welfare-improving capacity payment –general case

We saw in section 5 and 6 that when the capacity target was not too high (i.e. no more than twice the equilibrium capacity), CP's welfare increased, at the expense of EO's security of supply. However, if the target in CP is so high that operational capacity in EO falls to 0, and EO's SoS target is low enough, such an integration can be welfare improving in the EO market.

First, market EO wants to maintain its SoS level:

$$\mathcal{L}_{eo}^T \geq \mathcal{L}_{eo}(k^T, 0) = \iint_{l_{cp} \geq k^T} l_{eo} f(l) dl + \iint_{\substack{l_{cp} \leq k^T \\ l_{cp} + l_{eo} > k^T}} (l_{cp} + l_{eo} - k^T)) f(l) dl \tag{141}$$

This pins down the minimum target k^T at which CP's CRM is so strong that EO's SoS standard is met even with zero local capacity. Assuming $\bar{P} = VoLL$, and T is large, welfare in EO is :

CP has no CRM yet:

$$W_{eo} = (\bar{P} - c) \iint_{l_{cp} + l_{eo} \leq K^{eq}} l_{eo} f(l) dl \tag{142}$$

$$\mathcal{L}_{eo} = \mathcal{L}_{eo}(\alpha K^{eq}, (1 - \alpha) K^{eq}) \tag{143}$$

CP has a CRM:

$$W_{eo} =(\bar{P}-c)\iint_{l_{cp}+l_{eo}\leq K^T} l_{eo}f(l)dl \tag{144}$$

$$\mathcal{L}_{eo} =\mathcal{L}_{eo}(k^T,0) \tag{145}$$

If $K^T > K^{eq}$ and EO meets its SoS target, CP's CRM improves EO's welfare.

I Markets of different sizes –correlated demand

The results of this paper remain valid for markets that would be of different sizes.

SR-CP: Normalize the market with strategic reserve SR to 1. Say that the market with capacity payment (B) has total demand p. We assume again that demand is symmetric, that is, at all times $l_{cp} = pl_{sr}$

If SR and CP have the same SoS standard (i.e. they require the same demand coverage, which translate into making sure that total capacity is equal to some percentage of total demand), the situation is very equivalent to what we had in section 5. We have that $k^i_{sr2} = k^i_{sr}$. We also have that $k^{i,T}_{sr2} = k^{i,T}_{sr} = k^i_{cp} = 1/pk^{i,T}_{cp2}$.

Price hits the cap if and only if $l_{sr} + l_{cp} > k_{sr} + k_{cp} \Rightarrow (1 + p)l_{sr} > k_{sr2} + pk^T$. Free entry yields (recalling $k^T = k_{cp}$):

$$\pi_{sr2} = 0 = (\bar{P}-c)\left[1 - F(\frac{pk^T_{sr2} + k_{sr2}}{1+p}))\right] - r$$

Assume $k^T_{sr2} \leq 2k^i_{sr}$. We have that $k_{sr2} = (1 + p)F^{-1}(1 - \frac{r}{\bar{P}-c}) - k^T_{cp2} = (1 + p)k^i_{sr} - pk^T_{cp} < k_{sr}$: even more strategic reserve will need to be provided for by SR consumers. The payment by consumers for the strategic reserve is:

$$CP_{sr} = r(k^T_{sr2} - k_{sr2}) - (\bar{P}-c)\left(\int_{k^i_{sr}}^{k^T_{cp2}}(l_{sr} + l_{cp} - k^T_{cp2} - k_{sr2})f(l_{sr})dl_{sr} + (1 - F(k^T_{sr2})(k^T_{sr2} - k_{sr2})\right)$$

Payments by consumers on the energy market is :

$$CM_{sr} = c\int_0^{k^i_{sr}} l_{sr}f(l_{sr})dl_{sr} + \bar{P}\int_{k^i_{sr}}^{k^T_{cp}} l_{sr}f(l_{sr})dl_{sr} + \bar{P}(1 - F(k^T_{sr2})k^T_{sr2}$$

Using the same calculations as in section 5, we find that total consumer payment is :

$$C_{sr2} = CP_{sr} + CM_{sr} = rk_{sr2}^T + c(1 - F(k_{sr2}^T)k_{sr2}^T - \bar{P}(1 - F(k_{sr2}^T)k_{sr2}^T - (\bar{P} - c)(F(k_{sr2}^T) - F(k_{sr}^i))k_{sr2} \tag{146}$$

$$+ c(\int_0^{k_{sr}^i} l_{sr} f(l_{sr}) dl_{sr} + \int_{k_{sr}^i}^{k_{cp}^T} l_{sr} f(l_{sr}) dl_{sr}) + \bar{P}(1 - F(k_{sr2}^T)k_{sr2}^T \tag{147}$$

$$+ (\bar{P} - c)(-\int_{k_{sr}^i}^{k_{cp}^T} ((1+p)l_{sr} - k_{cp2}^T - k_{sr2}) f(l_{sr}) dl_{sr} + \int_{k_{sr}^i}^{k_{cp}^T} l_{sr} f(l_{sr}) dl_{sr}) \tag{148}$$

$$= C_{sr,cp}^i + (\bar{P} - c) \int_{k_{sr}^i}^{k_{cp}^T} (k_{cp2}^T - pl_{sr}) f(l_{sr}) dl_{sr} \tag{149}$$

$$= C_{sr,cp}^i + (\bar{P} - c) \int_{k_{sr}^i}^{k_{cp}^T} (pk_{cp}^T - pl_{sr}) f(l_{sr}) dl_{sr} \tag{150}$$

$$= C_{sr} + (p-1)(\bar{P} - c) \int_{k_{sr}^i}^{k_{cp}^T} (k_{cp}^T - l_{sr}) f(l_{sr}) dl_{sr} \tag{151}$$

Rather unsurprisingly, the bigger the neighbouring market CP, the bigger the increase in costs for market SR. The cost increment is proportional to the size of the neighbouring market p.

EO-CP: Similar calculations show that the only difference is that CP can "kill" more (less) capacity in its neighbouring markets if EO is bigger (smaller). That is, the condition of non-negativity of foreign operational markets is less (more) likely to bind.

SR-EO: The results are similar to the case with markets of same size. If SR is bigger (smaller), EO enjoys more (less) "zero-welfare cost" security of supply and its operational capacity remains unchanged. If EO is bigger (smaller), SR enjoys more (less) transfer from EO, to alleviate the cost of its strategic reserve. If EO size is normalized to 1 and SR size is p, the SoS increment in EO can be found by replacing k_{sr}^T by pk_{sr}^T in the expression found in appendix B.

J Interconnected SR/SR with different SoS standards – correlated demand

Take two markets with a strategic reserve SR1 and SR2. By construction, the strategic reserve does not have an impact on the electricity price, in either market. For simplicity, we take the case of a large interconnection capacity, and symmetric demand. As those markets are integrated, we must have $k_{sr1} = k_{sr2} = k_{sr}$. The strategic reserve of a market may be used for exports when the importer has exhausted its operational resources and strategic reserves, and the exporter has spare capacity. The economics of the importer's operational capacity remains unchanged, but it enjoys greater SoS thanks to its neighbour. The exporters gets extra revenues. Thus, interconnection is mutually beneficial: the low SoS standard market (say SR2) will need to build even less capacity, while the high SoS market SR1 will enjoy greater revenues through exports.

To maintain its level of SoS, market SR1 needs to keep $k_{sr1}^T = k_{sr1}^{i,T} = k_{sr}^T$, as it cannot count on SR2's capacity. Capacity k_{sr2}^T in 2 after integration with SR is such that its SoS level is maintained. With $\bar{k} = \frac{k_{sr1}^T + k_{sr2}^T}{2}$, we must have:

$$\int_{k_{sr2}^{i,T}}^{1} (l - k_{sr2}^{i,T}) f(l) dl = 2 \int_{\bar{k}}^{k_{sr1}^T} (l - \bar{k}) f(l) dl + \int_{k_{sr1}^T}^{1} (l - k_{sr2}^T) f(l) dl \tag{152}$$

$$\Leftrightarrow \int_{k_{sr2}^{i,T}}^{1} (l - k_{sr2}^{i,T}) f(l) dl = 2 \int_{\bar{k}}^{k_{sr1}^T} (l - \bar{k}) f(l) dl + \int_{k_{sr1}^T}^{1} (l - (2\bar{k} - k_{sr1}^T)) f(l) dl \tag{153}$$

$$\Leftrightarrow \int_{k_{sr2}^{i,T}}^{1} (l - k_{sr2}^{i,T}) f(l) dl + \int_{k_{sr1}^T}^{1} (l - k_{sr1}^T)) f(l) dl = 2 \int_{\bar{k}}^{1} (l - \bar{k}) f(l) dl \tag{154}$$

Given that $k \to EC(k) = \int_k^1 (l - k) f(l) dl$ is a strictly decreasing function, we have that $k_{sr2}^{i,T} < \bar{k} < k_{sr1}^{i,T}$[17].

Market 1 gets incremental revenues from high-priced exports:

$$(\bar{P} - c) \left(\int_{k_{sr2}^T}^{\bar{k}} (l - k_{sr2}^T) f(l) dl + \int_{\bar{k}}^{k_{sr1}^T} (k_{sr1}^T - l) f(l) dl \right) > 0$$

Decreased capacity needs in market SR2 translates into a cost reduction: less (unprofitable) strategic reserve needs to be subsidized while the expected demand coverage is maintained. The cost reduction is:

$$r(k_{sr2}^{i,T} - k_{sr2}^T) - (\bar{P} - c) \left(\int_{k_{sr2}^T}^{\bar{k}} (l - k_{sr2}^T) f(l) dl + \int_{\bar{k}}^{k_{sr1}^T} (k_{sr1}^T - l) f(l) dl \right) \tag{155}$$

$$= r(k_{sr1}^T + k_{sr2}^{i,T} - 2\bar{k}) - (\bar{P} - c) \left(\int_{k_{sr2}^T}^{\bar{k}} (l - k_{sr2}^T) f(l) dl + \int_{\bar{k}}^{k_{sr1}^T} (k_{sr1}^T - l) f(l) dl \right) > 0 \tag{156}$$

Hence, integration is mutually beneficial. Note that 2 may switch to an EO paradigm, if $k_{sr2}^T \leq k_{sr2} = k_{sr} \Leftrightarrow \bar{k} \leq \frac{k_{sr1}^{i,T} + k_{sr}}{2}$. This is coherent with our results in section 6, where we saw that an EO/SR integration is mutually beneficial.

Note also that the total welfare gains correspond to the decrease in investment costs in market

[17] $EC(k)$ being convex we can also say that $k_{sr2}^T < \bar{k} < \frac{k_{sr1}^T + k_{sr2}^{i,T}}{2}$

SR2:

$$r(k_{sr2}^{i,T} - k_{sr2}^{T}) = r(k_{sr2}^{i,T} + k_{sr1}^{i,T} - 2\bar{k}) > 0$$

Total welfare is thus increased, due to increased utilization rate of capacity in market SR1. It benefits market SR1 through high-priced exports, and market SR2 through reduced need for a local strategic reserve. Given that strategic reserve has a positive value on both markets, in a setting where SoS would be a "soft" target, there might me under-procurement.

K Interconnected CP/CP with different SoS standards – correlated demand

The situation is a bit different with CP/CP integration. Indeed any support to capacity in the form of a payment modifies the price signal.

For simplicity, we assume symmetric demand. Assuming there is a large interconnection capacity between countries $CP1$ and $CP2$, the price signal will be same in both countries: in equilibrium, the capacity payment must be the same in both markets:

$$m_{cp1} = m_{cp2} = r - (\bar{P} - c)(1 - F_l(\bar{K}^{eq}))$$

Where F_l is the CDF of total demand, and K^{eq} is the total level of capacity.

Market CP1 (market CP2) wants to maintain a SoS level of $\mathcal{L}_1$ ($\mathcal{L}_2$), jointly pinning down k_{cp1} and k_{cp2}.

As in the previous section, CP2 wants to maintain its curtailment level:

$$\mathcal{L}_{cp2}^{i} = \mathcal{L}_{cp2} \tag{157}$$

$$\Leftrightarrow \int_{k_{cp2}^{i,T}}^{1} (l - k_{cp2}^{i,T}) f(l) dl + \int_{k_{cp1}^{T}}^{1} (l - k_{cp1}^{T})) f(l) dl = 2 \int_{\bar{k}}^{1} (l - \bar{k}) f(l) dl \tag{158}$$

Market CP1 gets incremental revenues from high-priced exports:

$$(\bar{P} - c) \left(\int_{\bar{k}}^{k_{cp1}^{T}} (k_{cp1}^{T} - l) f(l) dl \right) > 0$$

Decreased capacity needs in market CP2 translates into a cost reduction: less capacity needs to be subsidized while the expected demand coverage is maintained. The cost reduction, given that demand coverage is the same before and after integration is[18]:

$$r(k_{cp2}^{i,T} - k_{cp2}^{T}) - (\bar{P} - c)\left(\int_{\bar{k}}^{k_{cp1}^{T}} (k_{cp1}^{T} - l)f(l)dl\right) \tag{159}$$

$$=(\bar{P} - c)\left((1 - F(k_{sr}))(k_{cp2}^{i,T} - k_{cp2}^{T}) - \int_{\bar{k}}^{k_{cp1}^{T}} (k_{cp1}^{T} - l)f(l)dl\right) \tag{160}$$

$$> 0 \tag{161}$$

Note that, again, aggregate welfare gains correspond to the decrease in investment costs in market 2, and are thus equal to those of the SR/SR case :

$$r(k_{cp2}^{i,T} - k_{cp2}^{T}) = r(k_{cp2}^{i,T} + k_{cp1}^{i,T} - 2\bar{k}) > 0$$

Again, total welfare is increased, due to increased utilization rate of capacity in market 1. It benefits market 1 through high-priced exports, and market 2 through a reduced capacity target. Thus if an EO market is forced, after a neighbour implemented a CP, to implement some capacity support as well, it should implement a CP rather than a SR. Given that part of the capacity support cost is borne by the other market, there might be over-procurement in the low-SoS market: CP2 might pretend its SoS target is greater than what it would optimally set if it were isolated (see section 7.3 for a formal analysis).

L Cross-border capacity payment required to maintain SoS in a neighbouring market

Given that a unilaterally implemented capacity payment has strong negative effects on neighbours' security of supply, a regional regulator might find it fair to require the capacity payment to be extended to the neighbours. Naturally, given that capacity in a market is not a perfect substitute to capacity in another market – be it from the point of view of the price effect or SoS effect, the payment need not be the same in both markets. Finding the appropriate cross-border payment required to maintain neighbours' SoS is very cumbersome – albeit numerically feasible. Thus, we'll study an extremely simplified framework that allows to see the main insight, summarized in the following proposition:

Proposition 9 *Even absent a contractual clause giving priority access to capacity, EO's capacity*

[18] NOTE: WE HAVEN'T BEEN ABLE TO PROVE positivity FORMALLY, YET. NUMERICAL APPLICATIONS CONFIRM THIS INTUITION . see C:Users Xavier SkyDrive Documents SR vs CP V2.nb

should receive a capacity payment to maintain EO's SoS. Capacity payments need not be the same in each market if cross-border capacities are imperfect market substitutes.

Proof. Assume that the level of SoS takes the following form:

$$SoS_{cp} = k_{cp} + \gamma_{eo} k_{eo} \tag{162}$$

$$SoS_{eo} = k_{eo} + \gamma_{cp} k_{cp} \tag{163}$$

, where for simplicity γ_{cp} and γ_{eo} is exogenous and $0 \leq \gamma_{cp}, \gamma_{eo} \leq 1$. That is, the level of security of supply increases in both capacity levels, but foreign capacity is derated by $\gamma_{cp/eo}$ – as it might not be available in case of concurrent system stress.

Then, the equilibrium level of capacity is given by:

$$k_{cp} = A - \alpha_{eo} k_{eo} + c m_{cp} \tag{164}$$

$$k_{eo} = A - \alpha_{cp} k_{cp} + c m_{eo} \tag{165}$$

, where $0 \leq \alpha_{eo} \leq 1$ and CP pays m_{cp} and m_{eo} to capacity in CP and EO respectively. That is, equilibrium capacities in CP and EO are partial substitutes.

Equations 162 and 163 pin the target capacities down:

$$k_{cp} = \frac{SoS_{cp} - \gamma_{eo} SoS_{eo}}{1 - \gamma_{cp}\gamma_{eo}} \; , \; k_{eo} = \frac{SoS_{eo} - \gamma_{cp} SoS_{cp}}{1 - \gamma_{cp}\gamma_{eo}} \tag{166}$$

Capacity payments are pinned down by 164 and 165:

$$m_{cp} = \frac{1}{c}\left(SoS_{cp} \frac{1 - \gamma_{cp}\alpha_{eo}}{1 - \gamma_{cp}\gamma_{eo}} + SoS_{eo} \frac{\alpha_{eo} - \gamma_{eo}}{1 - \gamma_{cp}\gamma_{eo}} - A \right) \tag{167}$$

$$m_{eo} = \frac{1}{c}\left(SoS_{eo} \frac{1 - \gamma_{eo}\alpha_{cp}}{1 - \gamma_{cp}\gamma_{eo}} + SoS_{cp} \frac{\alpha_{cp} - \gamma_{cp}}{1 - \gamma_{cp}\gamma_{eo}} - A \right) \tag{168}$$

Unsurprisingly, the required payment is decreasing in the effectiveness of the payment on investment incentive (parameter c). It is increasing in the local SoS target. The impact of the foreign SoS is ambiguous. If the (positive) impact of capacity on a foreign SoS is weaker than the (negative) impact on investment incentive (i.e. $\gamma_{eo} \leq \alpha_{eo}$), then m_{cp} is increasing in foreign SoS: market CP need to heavily subsidize its capacity and EO's, to increase its SoS and keep EO's SoS at its prevailing level.

Note that the capacity payment in EO is strictly positive. The difference in payment is :

$$m_{cp} - m_{eo} = \frac{1}{c(1-\gamma_{cp}\gamma_{eo})}\left(SoS_{cp}(1+\gamma_{cp}(1-\alpha_{eo})-\alpha_{cp}) - SoS_{eo}(1+\gamma_{eo}(1-\alpha_{cp})-\alpha_{eo})\right) \quad (169)$$

Unsurprisingly, the difference increases in SoS_{cp} and decreases in SoS_{eo}. Note that the difference is decreasing in α_{cp}: if CP's local capacity translates in a strong decrease in equilibrium capacity in EO, the payment in EO will have to be reinforced. Conversely, the difference is increasing in γ_{cp}, meaning that if CP's capacity participates strongly to EO's SoS, payment in EO can be relaxed. As a sanity check, note that if foreign capacity are perfect substitute in the energy market ($\alpha_{cp} = \alpha_{eo} = 1$)), the payment has to be same in both market, just like we found in 5.1 when demands were correlated and transmission was never biding. In the likely case where $\alpha_{cp} = \alpha_{eo} = \alpha$, we have:

$$m_{cp} - m_{eo} = \frac{1-\alpha}{c(1-\gamma_{cp}\gamma_{eo})}\left(SoS_{cp}(1+\gamma_{cp}) - SoS_{eo}(1+\gamma_{eo})\right) \quad (170)$$

, meaning that when CP's capacity participates to EO's SoS (large γ_{cp}), the "compensation" payment can be lower in EO. Intuitively, if CP secures a control right on EO's capacity (γ_{eo} increases), the payment in EO will need to be greater.

■

M Graphic representation of supply and demand balances

Graphs for perfectly symmetric demand, distributed on $[0,1]$, infinite transmission capacity.

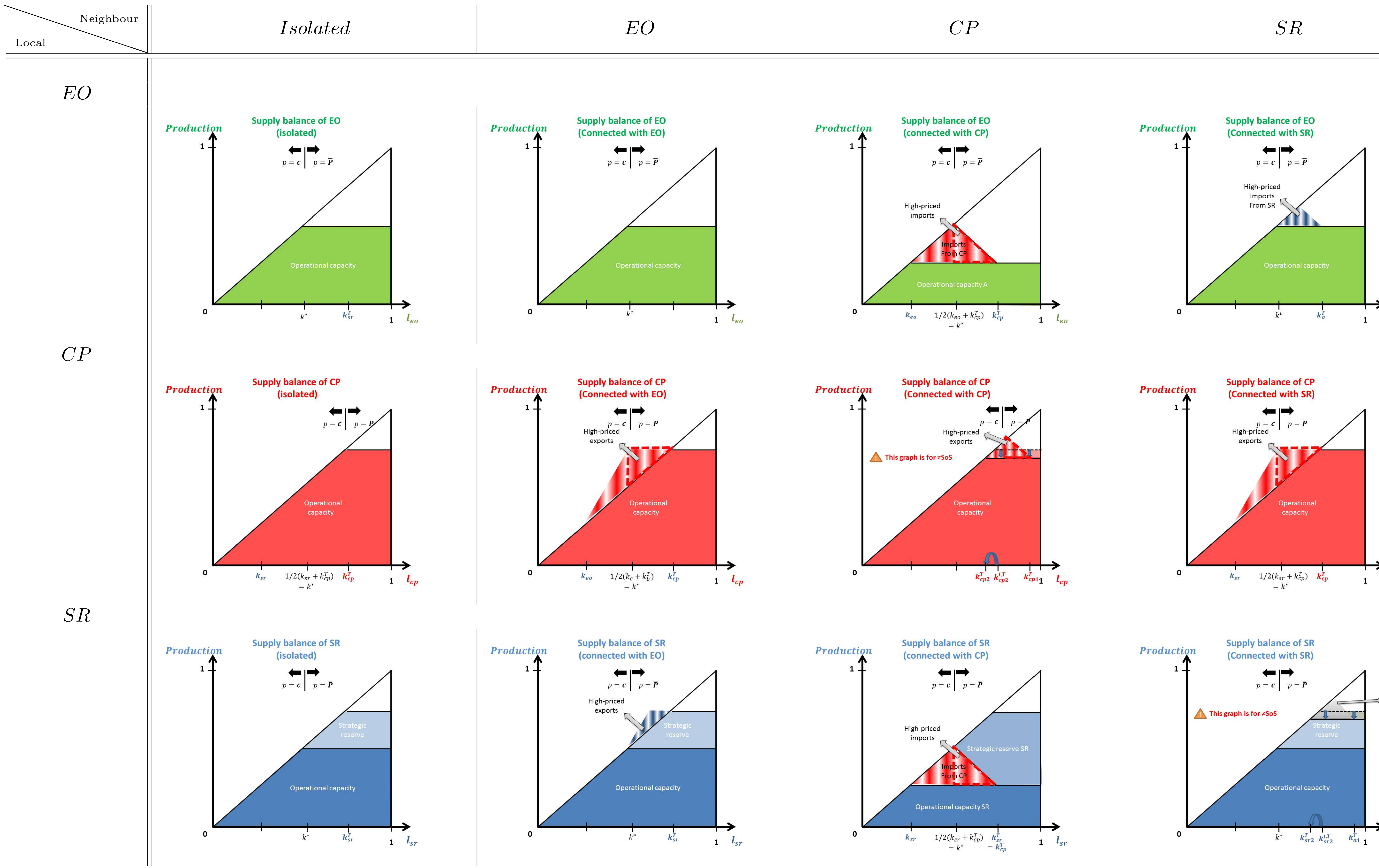


Figure 12: Supply as a function of demand. Perfectly correlated demand.