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

Online Appendix

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Abstract

This documents gathers the extensions of the main paper

OA.1 Interconnected SR/CM markets – symmetric markets

The price vector $P = (p_{SR}, p_{CM})$, exports and cross-border profits, in the general case where markets are interconnected with a transmission line of capacity T, is illustration in figure 1.

[Figure 1 about here.]

The key phenomenon we want to highlight is that when demand exceeds operational capacity in SR, but not in CM, CM 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, only then, SR starts activating its reserve capacity. Then, SR consumers will pay for high-priced imports from CM, while they could in theory use more of SR's reserve

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capacity that remains idle otherwise. SR's total capacity is under-utilized and there is cross-subsidization (see figure 2).

[Figure 2 about here.]

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/CM case, it happens if and only if $T > \frac{\bar{k}-k_{SR}}{2} \Leftrightarrow T > \bar{k} - k^i_{SR}$.

Transmission is never binding

A key property of a SR, is that operational capacity, and price setting are not affected. Hence, free-entry conditions and the resulting equilibrium capacity are same as in the EO/CM case (see Table 2).

Market with a strategic reserve

Free entry yields (recalling $\bar{k} = k_{CM}$):

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

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

Recalling that $\frac{\bar{k}+k_{SR}}{2} = k^*$, we observe that the cost increment corresponds to the welfare cost of SoS found in Section 4: 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.

[1] in fact, as we will see later, the costs of the strategic reserve will double: the required capacity is twice what it used to be in the isolated case: $k^{SR}_{SR} = \bar{k} - k_{SR} = 2(\bar{k} - k^i_{SR}) = 2k^{i,SR}_{SR}$

Net surplus is thus:

$$
\begin{aligned}
W_{SR} &= W_{SR}^{i} - \overbrace{(\bar{P} - c)\int_{\frac{\bar{k}+k_{SR}}{2}}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR}}^{W_{EO}^{*} - W_{EO}^{i}} \\
&= W_{EO}^{*} - 2(W_{EO}^{*} - W_{SR}^{i})
\end{aligned}
$$

We have assumed here that $\bar{k} \leq 2k_{SR}^{i}$, such that operational capacity in SR is non-negative. In the limit case $\bar{k} = 2k_{SR}^{i}$, we habe $k_{SR} = 0$: the market does not build any capacity, and all capacity needs to be provided for by the TSO, in the form of a strategic reserve. We just saw that net surplus in SR was reduced. However, Appendix OA.8 shows that a necessary (not sufficient) condition for the SR/CM integration to increase net surplus in SR, is that (1) $\bar{k} > 2k_{SR}^{i}$ and (2) $k_{SR} = 0$, such that there is no "market" capacity in SR, but the capacity excess in CM is so large that SR meets its SoS target anyways.

Market with a capacity market

Free entry yields

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

Comparing with free-entry in market SR, we find that $m = 0$. The same calculations as in the EO/CM case yield $W_{CM} = W_{EO}^{*}$.

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

Net surplus in CM is :

$$\begin{aligned}W_{CM} &= W_{SR}^i + (\bar{P} - c) \int_{\frac{k_{CM}+k_{SR}}{2}}^{k_{CM}} (k_{CM} - l_{SR}) f(l_{SR}) dl_{SR} \\ &= W_{EO}^* \\ &= W_{SR} + 2\Delta W^i(\bar{k})\end{aligned}$$

Figure 3 illustrates what happens in the short and longer term, when SR and CM get interconnected.

[Figure 3 about here.]

Unsurprisingly, the total net surplus remains unchanged compared to the isolated case: there is still a need to build $2\bar{k}$ 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 CM, as the reserve capacity does not sell any energy in market CM, while market CM'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).

Cost of SoS

In this subsection, we relax the assumption that SR and CM have the same SoS standards: Now we allow $k_{CM}^T \neq k_{SR}^T = \bar{k}$. We showed that the marginal *social* cost of capacity in SR, is weakly greater than in the isolated case. We now propose to go into more details. When the capacity target $\bar{k}$ 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[2] (very high target, exceeding CM's). For intermediate levels of capacity target, the overall social cost is greater than in the isolated case. First, the implementation of a capacity market in CM depresses market prices in SR, and therefore investment in market SR: $k_{SR}(\bar{k})$ is a decreasing function of $\bar{k}$. If $k_{SR}(\bar{k}) < \bar{k} < k^i_{SR}$, SR will have to back up reserve capacity, while it didn't need to intervene when before CM implemented its capacity market[3]. More precisely, if $k_{SR}(\bar{k}) < \bar{k} < k^i_{SR}$, 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 called when local demand exceeds local capacity.

In short, an interconnection with CM may force SR to implement a strategic reserve to meet its adequacy target, and this comes at a higher cost than if the markets were isolated. Interestingly, the cost of capacity in CM is exactly 0, as long as operational capacity in SR k_{SR} exceeds 0.[4] Indeed, even the smallest subsidy for capacity in CM makes it more competitive than market SR's operational capacity: the latter is displaced by the former.

Figure 4 shows SR's marginal cost of capacity is greater for intermediate levels of capacity.

[2]here we implicitly assume that SR curtails exports before it activates its strategic reserve. If SR were maintaining exports, SR would increase CM's SoS, and in turn CM would decrease its capacity target. This relaxation of a neighbors 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 CM'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.

[3]note that the same holds for market EO if $k_{EO}(\bar{k}) < k^T_{EO} < k^*$

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

Marginal social cost of an additional unit of reserve capacity:

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

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

[Figure 4 about here.]

Figure 5 relates the cost of capacity to demand coverage. First graph shows that integrating an EO market with a CM 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 CM 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.

[Figure 5 about here.]

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

Proposition 1 *When a market with a strategic reserve is interconnected with a symmetric market, where the capacity target is achieved through a capacity market, the latter market meets its SoS target at zero net-surplus cost, transfering the burden to the strategic reserve neighbor. Overall net surplus 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 CM 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 CM's firms or CM's TSO, this extra source of revenue is used to decrease the required capacity markets in CM and alleviate consumers bill. Market CM is better off than market SR, even when transmission capacity is small.

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

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

$$\pi_{CM} = (\bar{P} - c)[1 - F(k_{CM} - T)] \tag{OA.2}$$

As before, r is the capacity cost in both markets. m is the capacity payment in market CM. Assume for the moment that CM (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^c_{SR}) or reserved (k^{cSR}_{SR}) 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:

$$\pi_{SR} = 0 = (\bar{P} - c)[1 - F(k^c_{SR} + T)] - r \Rightarrow k^c_{SR} = F^{-1}(1 - \frac{r}{\bar{P} - c}) - T$$

Note that $k^c_{SR} = F^{-1}(1 - \frac{r}{\bar{P}-c}) - T = k^i_{SR} - T > k^i_{SR} - \frac{\bar{k}-k_{SR}}{2} = k^i_{SR} - \bar{k} + \frac{\bar{k}+k_{SR}}{2} > 2k^i_{SR} - \bar{k}$. Hence $k_{SR} < k^c_{SR} < k^i_{SR}$. Strategic reserves are used during scarcity. The expected revenues are :

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

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

$$CM^c = r * (\bar{k} - k_{SR}) - \mathbb{E}[SR]$$

Expected payments by consumers on the energy market are:

$$CM^c_{SR} = c \int_0^{k_{SR}+T} l_{SR} f(l_{SR}) dl_{SR} + \bar{P} \left(\int_{k_{SR}+T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} + (1 - F(\bar{k}))\bar{k} \right) \tag{OA.3}$$

Total costs are :

$$C^c_{SR} = CM^c_{SR} + CM^c_{SR} = c\int_0^{k_{SR}+T} l_{SR} f(l_{SR}) dl_{SR} + c\left(\int_{k_{SR}+T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} + (1-F(\bar{k}))\bar{k}\right)$$
$$+ (\bar{P}-c)\left(\int_{k_{SR}+T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} + (1-F(\bar{k}))\bar{k}\right) + r\bar{k} - rk_{SR}$$
$$- (\bar{P}-c)\Big(\int_{k_{SR}+T}^{k_{CM}-T} (l_{SR} - (k_{SR}+T)) f(l_{SR}) dl_{SR}$$
$$+ \int_{k_{CM}-T}^{k_{CM}} (2l_{SR} - (k_{SR}+\bar{k})) f(l_{SR}) dl_{SR} + (1-F(\bar{k}))(\bar{k}-k_{SR})\Big)$$
$$= C^i_{SR,CM} - (\bar{P}-c)k_{SR}[F(k_{CM}) - F(k_{SR}+T)]$$
$$+ (\bar{P}-c)\left(\int_{k_{SR}+T}^{k_{CM}-T} (k_{SR}+T) f(l_{SR}) dl_{SR} - \int_{k_{CM}-T}^{k_{CM}} (l_{SR} - (k_{SR}+\bar{k})) f(l_{SR}) dl_{SR}\right)$$
$$= C^i_{SR,CM} + (\bar{P}-c)\Bigg((k_{SR}+T)(F(k_{CM}-T) - F(k_{SR}+T)) + k_{SR}(F(k_{SR}+T) - F(k_{CM}))$$
$$- \int_{k_{CM}-T}^{k_{CM}} (l_{SR} - (k_{SR}+\bar{k})) f(l_{SR}) dl_{SR}\Bigg)$$
$$= C^i_{SR,CM} + (\bar{P}-c)\left(\int_{k_{CM}-T}^{k_{CM}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR} + T(F(k_{CM}-T) - F(k_{SR}+T))\right)$$
$$> C^i_{SR,CM}$$

Market CM

Similarly, we must have

$$rk_{CM} = m^c k_{CM} + \Pi_{CM}$$
$$= mk_{CM} + (\bar{P}-c)\left[(1 - F(k_{CM}-T))\, k_{CM} + (F(k_{CM}-T) - F(k_{SR}+T))T\right]$$
$$\Rightarrow m^c = r - (\bar{P}-c)[1 - F(k_{CM}-T) + (F(k_{SR}+T) - F(k_{CM}-T))T/k_{CM}]$$

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

$$m^c = m^i - (\bar{P} - c)\left[(F(k_{CM}) - F(k_{CM} - T)) + (F(k_{CM} - T) - F(k_{SR} + T))T/\bar{k}\right] < m^i \tag{OA.4}$$

$$m^c = m^i - (\bar{P} - c)\left[(F(\frac{k_{CM} + k_{SR}}{2}) - F(k_{CM} - T)) + (F(k_{CM} - T) - F(k_{SR} + T))T/\bar{k}\right] > 0 \tag{OA.5}$$

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

$$CM^c_{CM} = mk_{CM} \tag{OA.6}$$

Expected payments on the energy markets are:

$$CM^c_{CM} = c\int_0^{k_{CM}-T} l_{SR}f(l_{SR})dl_{SR} + \bar{P}\left(\int_{k_{CM}-T}^{\bar{k}} l_{SR}f(l_{SR})dl_{SR} + (1 - F(\bar{k}))\bar{k}\right) \tag{OA.7}$$

Total costs are:

$$
\begin{aligned}
C^c_{CM} =&CM^c_{CM} + CM^c_{CM} = c\int_0^{k_{CM}-T} l_{SR} f(l_{SR}) dl_{SR} + c\int_{k_{CM}-T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} + c(1-F(\bar{k}))\bar{k} \\
&+ (\bar{P}-c)\left(\int_{k_{CM}-T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} + (1-F(\bar{k}))\bar{k}\right) \\
&+ rk_{CM} - (\bar{P}-c)[(1-F(k_{CM}-T))k_{CM} + (F(k_{CM}-T) - F(k_{SR}+T))T] \\
=&C^i_{SR,CM} - (\bar{P}-c)\Big[(F(k_{CM}) - F(k_{CM}-T))k_{CM} - \int_{k_{CM}-T}^{\bar{k}} l_{SR} f(l_{SR}) dl_{SR} \\
&\qquad + T(F(k_{CM}-T) - F(k_{SR}+T))\Big] \\
=&C^i_{SR,CM} - (\bar{P}-c)\left[\int_{k_{CM}-T}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR} + T(F(k_{CM}-T) - F(k_{SR}+T))\right] \\
>&C_{CM} \text{ and } < C^i_{SR,CM}
\end{aligned}
$$

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

Overall net surplus

Again, and for the same reasons as in the previous subsection, SR's extra costs, and CM'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 design, it would be better off with little transmission capacity.

Transmission rights

Here we implicitly assumed that market CM (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 CM owns the remainder $1-\alpha$), the consumer costs are modified as follows:

$$C_{SR}^{c} = C_{SR,CM}^{i} + (\bar{P}-c)\left[\overbrace{\int_{k_{CM}-T}^{k_{CM}} (\bar{k}-l_{SR})f(l_{SR})dl_{SR}}^{B's\ undercutting} + (1-\alpha)\overbrace{T(F(k_{CM}-T)-F(k_{SR}+T))}^{congestion\ rent}\right] \tag{OA.8}$$

$$C_{CM}^{c} = C_{SR,CM}^{i} - (\bar{P}-c)\left[\int_{k_{CM}-T}^{\bar{k}} (\bar{k}-l_{SR})f(l_{SR})dl_{SR} + (1-\alpha)T(F(k_{CM}-T)-F(k_{SR}+T))\right] \tag{OA.9}$$

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 CM, and gets the congestion rents. However, market SR is still over-paying CM firms, when CM exports to SR at high prices, and transmission is not yet congested. Overall net surplus remains unchanged.

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

Proposition 2 *When transmission is binding, a market with a capacity market will decrease its SoS costs, through a partial transfer of the burden to its strategic reserve neighbor, even if the country with a strategic reserve owns the transmission rights.*

OA.2 Interconnected SR/CM 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 Appendix C, Define $l = (l_{SR}, l_{CM})$. Denote by $f(l_{SR}, l_{CM})$ 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: $1 - F_l(k_{CM}^T + k_{SR}) = \frac{r}{P-c} = 1 - F_l(k_{SR}^{eq} + k_{CM}^{eq})$. Therefore, again, we have that operational capacity in SR acts as a buffer, such that total capacity remains optimal: $k_{SR} = k_{SR}^{eq} + k_{CM}^{eq} - k_{CM}^T = K^{eq} - k_{CM}^T$. 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 CM want to increase their SoS, with would translate into the construction of Δ_{SR} and Δ_{CM} strategic reserve. Define $\Delta_{SR} + \Delta_{CM} = 2\Delta$. Assume that transmission is never binding and that market SR uses its strategic reserve to serve demand in market CM, when the latter is tight. First, observe that if both countries have the same capacities (either supported with a CM 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 CM implements a capacity market. It will provide support until its capacity allows demand coverage to reach a given value. Then, if market SR adjusts its capacity such that $k_{CM} = k_{SR}^T = k_{SR}^{eq} + \Delta_{SR}$, demand coverage in SR remains identical as total demand coverage is maintained and CM's demand coverage is maintained. Therefore if two integrated countries have the same SoS target ($\Delta_{SR} = \Delta_{CM}$), 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:

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

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

$$
\begin{aligned}
\frac{RE(k_{a=SR}^T, k_{b=CM}^T)}{\bar{P} - c} = & \iint_{\substack{K^{eq} + 2\Delta \leq l_{SR} + l_{CM} \\ k_{CM}^T > l_{CM}}} (k_{CM}^T - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& - \iint_{\substack{K^{eq} + 2\Delta \leq l_{SR} + l_{CM} \\ k_{SR}^T > l_{SR}}} (k_{SR}^T - l_{SR}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& + \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} > l_{CM}}} (k_{CM} - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& - \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} < l_{CM}}} (l_{CM} - k_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}
\end{aligned}
$$

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

$$
\begin{aligned}
= & \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} > l_{CM} \ , \ k_{SR}^T > l_{SR}}} (k_{CM} - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& + \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} > l_{CM} \ , \ k_{SR}^T < l_{SR}}} (k_{CM} - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& - \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} < l_{CM}}} (l_{CM} - k_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
= & \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} > l_{CM} \ , \ k_{SR}^T > l_{SR}}} (k_{CM} - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& + \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} > l_{CM} \ , \ k_{SR}^T < l_{SR}}} (k_{CM} - l_{CM} + k_{SR}^T - l_{SR}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& + \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{SR}^T < l_{SR}}} (l_{SR} - k_{SR}^T) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\
& - \iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{CM} < l_{CM}}} (l_{CM} - k_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}
\end{aligned}
$$

By symmetry, the last two terms cancel out:

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

$$+ \overbrace{\iint_{\substack{K^{eq} \leq l_{SR} + l_{CM} \leq K^{eq} + 2\Delta \\ k_{SR}^T < l_{SR}}} (K^{eq} + 2\Delta - (l_{SR} + l_{CM})) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}}^{net\ benefit\ from\ selling\ into\ a\ tight\ neighboring\ market}$$

$$>0$$

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

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 $-\Delta W_{sr+cm}$, normalized by the instantaneous scarcity rent $\bar{P} - c$ is:

$$\frac{-\Delta W_{sr+cm}}{\bar{P} - c} = (\bar{P} - c) \iint_{K^{eq} < l_{SR} + l_{CM} < K^{eq} + 2\Delta} (K^{eq} + 2\Delta - (l_{SR} + l_{CM}))\, f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}$$

We have seen that if markets are perfectly integrated, consumers pay the same price in the energy market CM and EO. We found that $m = 0$: the capacity support costs nothing to CM consumers. That is, only SR consumers are paying for the additional capacity. Thus, they pay for both CM and SR's SoS. SR needs to fund 2Δ capacity. The cost of support in SR is:

$$\begin{aligned} \frac{-\Delta SR_{CM}}{\bar{P} - c} =& 2 * \Delta(1 - F(K^{eq})) - (\bar{P} - c)\Big(2\Delta \iint_{K^{eq} + 2\Delta < l_{SR} + l_{CM}} f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} \\ &+ \iint_{K^{eq} < l_{SR} + l_{CM} < K^{eq} + 2\Delta} \Big(l_{SR} + l_{CM} - K^{eq}\Big) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}\Big) \\ =& \frac{-\Delta W_{sr+cm}}{\bar{P} - c} \end{aligned} \quad \text{(OA.10)}$$

That is, market CM gets all its SoS financed by SR consumers: again we observe that all the welfare costs of implementation of a SoS standard with a CM strategy has been transferred to the SR neighbor. CM increases its SoS, and maintains its welfare level at the expense of market SR. Note that $\Delta SR_{CM} = 2RE(k^T_{a=SR}, k^T_{b=CM})$. This means the whole cost of SoS is borne by the consumers in the market with a strategic reserve, due to CM's cross-border rent extraction. The rationale is fairly intuitive; by giving a slight competitive advantage to its operational capacity, CM attracts investors. SR compensates the loss by increasing its strategic reserve. From CM'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 CM'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). CM gets the remaining $1 - \alpha_e$ ($1 - \alpha_i$).

Rent extraction from SR towards CM is:

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

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

$$+ \iint_{\substack{K^{eq} < l_{SR} + l_{CM} \\ \bar{k} - T < l_{CM} < \bar{k}}} (\bar{k} - l_{CM}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM} - \iint_{\substack{K^{eq} < l_{SR} + l_{CM} \\ \bar{k} - T < l_{SR} < \bar{k}}} (\bar{k} - l_{SR}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}$$

$$- \iint_{\substack{K^{eq} < l_{SR} + l_{CM} \leq 2\bar{k} \\ \bar{k} < l_{CM} < \bar{k} + T}} (l_{CM} - \bar{k}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}$$

$$- T \iint_{\substack{k_{SR} - T < l_{SR} \leq \bar{k} - T \\ \bar{k} + T \leq l_{CM}}} (l_{CM} - \bar{k}) f(l_{SR}, l_{CM}) dl_{SR} dl_{CM}$$

A wise allocation of the transmission rights may allow to correct for the unwanted monetary tranfers from SR to CM. 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 CM). 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 $RE(k^T_{a=SR}, k^T_{b=CM}, T, \alpha = (1,1))$. 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 $T \to 0$, $RE(k^T_{a=SR}, k^T_{b=CM}, T, \alpha = (1,1))$ 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 $T < Min[\bar{k}, \bar{l} - \bar{k}]$, SR is no longer prejudiced.

OA.3 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 CM), total net surplus 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 net surplus 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. $T > \frac{\bar{k}-k^i_{SR}}{2}$).

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

Total costs for consumers in SR equal the costs in the isolated case, minus some high priced exports when EO is tight while SR is not (based on local capacity):

$$C_{SR} = C^i_{SR,CM} - (\bar{P} - c)\Bigg(\overbrace{\int_{k^i_{SR}}^{\frac{k^i_{SR}+\bar{k}}{2}} (l_{SR} - k^i_{SR}) f(l_{SR}) dl_{SR}}^{EO\ is\ tight,\ overall\ system\ is\ not} + \underbrace{\int_{\frac{k^i_{SR}+\bar{k}}{2}}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR}}_{EO\ is\ tight,\ SR\ is\ not,\ overall\ system\ is} \Bigg)$$

Market EO

Since $l_{EO} = l_{SR}$, any imports will be high-priced.[5] If $\bar{P} = VoLL$, society EO is indifferent between paying $\bar{P}$ for some imports and curtailing some of its consumers: net surplus 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 increase in gross surplus:

$$C_{EO} = C^i_{EO} + (\bar{P} - c)\left(\int_{k^i_{SR}}^{\frac{k^i_{SR}+\bar{k}}{2}} (l_{SR} - k^i_{SR}) f(l_{SR}) dl_{SR} + \int_{\frac{k^i_{SR}+\bar{k}}{2}}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR} \right)$$

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

$$\begin{aligned} \mathcal{L}_{EO} &= \int_{\frac{k^*+\bar{k}}{2}}^{\bar{k}} (2l_{EO} - 2k^*) f(l_{EO}) dl_{EO} + \int_{\bar{k}}^{1} (l_{EO} - k_{EO}) f(l_{EO}) dl_{EO} \\ &= \mathcal{L}^* - \int_{k^*}^{\frac{k^*+\bar{k}}{2}} (l_{EO} - k^*) f(l_{EO}) dl_{EO} - \int_{\frac{k^*+\bar{k}}{2}}^{\bar{k}} (\bar{k} - l_{EO}) f(l_{EO}) dl_{EO} < \mathcal{L}^* \end{aligned}$$

[5]If $l_{SR} \leq k_{EO}$ both markets are loose and $P_{SR} = P_{EO} = c$, $t = 0$. If $l_{SR} > \bar{k}$, both markets are tight and curtail: $P_{SR} = P_{EO} = \bar{P}$, $t = 0$. If $k_{EO} < l_{SR} \leq \bar{k}$ 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

Net surplus

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 increment in net surplus in SR. Since price cap equals the VoLL, EO is indifferent to being connected with SR or not. There is therefore an overall increase in net surplus, driven by SR's cost reduction.

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

$$\left(\int_{k^i_{SR}}^{\frac{k^i_{SR}+\bar{k}}{2}} (l_{SR} - k^i_{SR}) f(l_{SR}) dl_{SR} + \int_{\frac{k^i_{SR}+\bar{k}}{2}}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR} \right) > 0$$

Therefore, we have the following proposition:

Proposition 3 *When a market with a strategic reserve has an energy-only neighbor, 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

Total costs for SR consumers equal the costs in the isolated case, minus some high priced exports when EO is tight while SR is not (based on local capacity):

$$C_{SR} = C^i_{SR,CM} - (\bar{P} - c) \Big(\int_{k^i_{SR}}^{k^i_{SR}+T} (l_{SR} - k_{SR}) f(l_{SR}) dl_{SR} + T(F(\bar{k} - T) - F(k^i_{SR} + T)) + \int_{\bar{k}-T}^{\bar{k}} (\bar{k} - l_{SR}) f(l_{SR}) dl_{SR} \Big)$$

Market EO

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

Net surplus

The increment in overall net surplus 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[6], 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.

OA.4 Interconnected EO/SR markets –general case

Again, if transmission is not binding, free entry yields: $1 - F_l(k_{CM}^T + k_{SR}) = \frac{r}{\bar{P}-c} = 1 - F_l(K^{eq})$. 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, with no decrease in net surplus. High-priced exports to EO will alleviate the burden to SR's consumers.

Assume that market SR uses its strategic reserve to serve demand in market EO,

[6] Again, EO gets additional demand coverage, with no decrease in net surplus

when the latter is tight. Net surplus in EO, compared to the EO/EO case is unchanged as operational capacities in both markets are unchanged, and all imports from the neighboring strategic reserve come at a price equal to VoLL. EENS in SR is decreased, down to SR's target:

$$
\begin{aligned}
\bar{\mathcal{L}}_{SR} =& \mathcal{L}_{EO}(k_{SR}, < k_{EO}) - \iint_{\substack{k_{SR} \leq l_{SR} \leq k_{SR}^T \\ k_{EO} \leq l_{EO}}} (l_{SR} - k_{SR}) f(l) dl \\
& - \iint_{\substack{k_{EO} - T \leq l_{EO} \leq k_{EO} \\ 2k_{SR} \leq l_{EO} + l_{SR} \leq k_{SR} + k_{SR}^T}} (l_{SR} + l_{EO} - 2k_{SR}) f(l) dl \\
& - \iint_{\substack{k_{SR} + T \leq l_{SR} \leq k_{SR}^T + T \\ l_{EO} \leq k_{EO} - T}} (l_{SR} + l_{EO} - 2k_{SR}) f(l) dl \\
& - (k_{SR}^T - k_{SR}) \left(\iint_{\substack{k_{SR}^T \leq l_{SR} \\ l_{EO} \geq k_{EO} - T \\ l_{EO} + l_{SR} > k_{SR} + k_{SR}^T}} f(l) dl + \iint_{\substack{k_{SR}^T + T \leq l_{SR} \\ l_{EO} \leq k_{EO} - T}} f(l) dl \right)
\end{aligned}
$$

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

$$
\begin{aligned}
\mathcal{L}_{EO}(\bar{k}, k_{EO}) =& \mathcal{L}_{EO}(k_{SR}, k_{EO}) - \iint_{\substack{k_{SR} - T \leq l_{SR} \leq k_{SR} \\ 2k_{SR} \leq l_{SR} + l_{EO}}} Min[T, k_{SR} - l_{SR}] l_{SR} - k_{SR}) f(l) dl \\
& - \iint_{\substack{k_{EO} \leq l_{EO} \leq k_{EO} + T \\ l_{EO} + l_{SR} \leq k_{SR} + k_{SR}^T \\ k_{SR} \leq l_{SR}}} (l_{EO} - k_{EO}) f(l) dl \\
& - T \iint_{\substack{k_{SR} \leq l_{SR} \leq k_{SR} + T \\ k_{EO} + T \leq l_{EO}}} f(l) dl + \iint_{\substack{\bar{k} - T \leq l_{SR} \leq \bar{k} \\ 2k_{SR} \leq l_{EO} + l_{SR}}} (\bar{k} - l_{SR}) f(l) dl
\end{aligned}
$$

The decrease in net surplus caused by the implementation of the strategic reserve is:

$$
\frac{\Delta W(\bar{k}, k_{EO})}{\bar{P} - c} = r k_{SR}^T - \underbrace{\mathcal{L}_{SR}(\bar{k}, k_{EO}) - \mathcal{L}_{EO}(k_{SR}, k_{EO})}_{\textit{energy served locally by SR capacity}} - \underbrace{\mathcal{L}_{EO}(\bar{k}, k_{EO}) - \mathcal{L}_{EO}(k_{SR}, k_{EO})}_{\textit{energy served abroad by SR capacity}}
$$

That is, the cost in terms of net surplus 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 net surplus is increased compared to a situation where exports from SR's strategic reserve would be forbidden. Net surplus in EO is unchanged, and SR gets additional cross-border sales revenues. The fundamental reason for this increase in net surplus is that the utilization rate of the strategic reserve has increased.

OA.5 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 neighbor. 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 $\bar{k}_{sr1} = k_{sr1}^{i,T} = k_{SR}^{T}$, as it cannot count on SR2's capacity. Capacity $\bar{k}_{sr2}$ in 2 after integration with SR is such that its SoS level is maintained. With $\bar{k} = \frac{\bar{k}_{sr1}+\bar{k}_{sr2}}{2}$, we must have:

$$
\begin{aligned}
&\int_{k_{sr2}^{i,T}}^{1}(l - k_{sr2}^{i,T})f(l)dl = 2\int_{\bar{k}}^{\bar{k}_{sr1}}(l-\bar{k})f(l)dl + \int_{\bar{k}_{sr1}}^{1}(l-\bar{k}_{sr2})f(l)dl \\
\Leftrightarrow &\int_{k_{sr2}^{i,T}}^{1}(l - k_{sr2}^{i,T})f(l)dl = 2\int_{\bar{k}}^{\bar{k}_{sr1}}(l-\bar{k})f(l)dl + \int_{\bar{k}_{sr1}}^{1}(l-(2\bar{k}-\bar{k}_{sr1}))f(l)dl \\
\Leftrightarrow &\int_{k_{sr2}^{i,T}}^{1}(l - k_{sr2}^{i,T})f(l)dl + \int_{\bar{k}_{sr1}}^{1}(l-\bar{k}_{sr1}))f(l)dl = 2\int_{\bar{k}}^{1}(l-\bar{k})f(l)dl
\end{aligned}
$$

Given that $k \to EC(k) = \int_k^1 (l-k)f(l)dl$ is a strictly decreasing function, we have that $k_{sr2}^{i,T} < \bar{k} < k_{sr1}^{i,T}$.[7]

Market 1 gets incremental revenues from high-priced exports:

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

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:

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

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

Note also that the overall gains in net surplus correspond to the decrease in investment costs in market SR2:

$$r(k_{sr2}^{i,T}-k_{sr2}^{T}) = r(k_{sr2}^{i,T}+k_{sr1}^{i,T}-2\bar{k}) > 0 \tag{OA.11}$$

Overall net surplus 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.

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

OA.6 No control on exports

We have assumed that TSOs may have the possibility to reduce export capacity. That is, if its system it tight, it can limit exports to avoid local curtailments or brownouts. Current national network codes allow such interventions.[8] This is however in direct contradiction with the Security of Supply directive (see Mastropietro et al. (2015) for an exposition of this problem). We assume in this section that the European Commission Security of Supply directive applies, and TSOs might not be allowed to reduce export capacity –

Luckily for our analysis, in real life in case of concomitant scarcity, 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 a 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.

[8]furthermore, TSOs may reduce transmission capacity on the basis of private information on grid stability and capacity booking. Potential abuses may thus prove difficult to idendify and regulate

Free entry conditions are:

$$r = \overbrace{\left(\frac{c}{1-\nu} - c\right) \iint_{\substack{k_{EO} < l_{EO} \leq k_{EO}+T \\ l_{CM}+l_{EO} \leq K^{eq}}} f(l)dl}^{\text{imports from lose CM}} + \overbrace{\left(\bar{P}(1-\nu) - c\right) \iint_{\substack{k_{EO}-T < l_{EO} \leq k_{EO} \\ l_{CM}+l_{EO} \geq K^{eq}}} f(l)dl}^{\text{Loose EO exports to tight CM}}$$
$$+ (\bar{P} - c) \left(\overbrace{\iint_{\substack{k_{EO}+T < l_{EO} \\ l_{CM} \leq k_{CM}-T}} f(l)dl}^{\text{transmission bottleneck}} + \overbrace{\iint_{\substack{l_{EO} \geq k_{EO}, l_{CM} \geq k_{CM}-T \\ l_{CM}+l_{EO} \geq K^{eq}}} f(l)dl}^{\text{high priced imports}} \right)$$

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

Hence, the capacity market is:

$$m = c\frac{\nu}{1-\nu} \left(\iint_{\substack{k_{EO} < l_{EO} \leq k_{EO}+T \\ l_{CM}+l_{EO} \leq K^{eq}}} f(l)dl - \iint_{\substack{k_{CM} < l_{CM} \leq k_{CM}+T \\ l_{CM}+l_{EO} \leq K^{eq}}} f(l)dl \right)$$
$$+ \nu\bar{P} \left(\iint_{\substack{k_{CM}-T < l_{CM} \leq k_{CM} \\ l_{CM}+l_{EO} \leq K^{eq}}} f(l)dl - \iint_{\substack{k_{EO}-T < l_{EO} \leq k_{EO} \\ l_{CM}+l_{EO} \geq K^{eq}}} f(l)dl \right)$$
$$+ (\bar{P} - c) \left(\iint_{\substack{k_{EO}+T < l_{EO} \\ l_{CM} \leq k_{CM}-T}} f(l)dl - \iint_{\substack{k_{CM}+T < l_{CM} \\ l_{EO} \leq k_{EO}-T}} f(l)dl \right)$$

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 CM 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 CM is more likely to export to EO due to its CRM-promoted capacity. Doing so, net surplus in EO is unchanged, while CM's profits increase by only $\bar{P}(1-\nu) - c$ by unit of energy sold (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 CM'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), the capacity market must increase. Indeed, capacity in CM is no longer a perfect substitute to capacity in EO. CM'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 CM to meet its target.

Abstracting from this small capacity market by CM to compensate for the transaction cost, the results will be exactly similar to those of Section 4 and Appendix C. Relaxing the "domestic preference" assumption, and introducing transmission losses takes us back to the domestic preference" results.

Thus, we have 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 CM to EO, even though prices are the same. This does not undermine our analysis: if power flows to EO instead of staying in CM in some states of the world, CM 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 CM cannot meet its target at all is discussed in Section 5.1.

OA.7 Controlling import capacity

A TSO could in theory reduce import capacity at all times, 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 the SoS in EO shrinks as T increases. Taking $T = 0$ effectively takes us to the isolated situation described in Section 3. However, this goes against the Security of Supply directive, and the current drive to open-trade in Europe. Then, consumer 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 CM and EO are unchanged. We thus focus on the case when a TSO would curtail high-priced imports only. A first comment is that it would be a bold measure: in the short term, curtailing high-priced imports would merely 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, which may be politically unacceptable.

Let us turn now to the long-run effects. Note that the price signals in EO is unaffected by import curtailment, as prices hit the cap whether TSOs contain exports or not. This means the target capacity in CM is the same as in the "laissez faire" case: $k_{CM} = \bar{k}$, as EO's import curtailment does not affect expected consumer curtailment in CM: capacity investments in either markets will be unaffected by the measure. Free-entry in CM yields:

$$m = r - (\bar{P} - c)\Big(\overbrace{\mathbb{P}(l_{CM} > \bar{k} + T, l_{EO} < k^*)}^{\substack{\textit{Transmission congested in} \\ EO \to CM \textit{ direction}}} + \overbrace{\mathbb{P}(l_{CM} > \bar{k}, l_{EO} > k^* - T, l_{CM} + l_{EO} > \bar{k} + k^* - T)}^{\substack{CM \textit{ and overall} \\ \textit{system are congested}}} \Big)$$

Note that the capacity payment is now greater than what we found when EO did not control import capacity. 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 CM'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 non-domestic market the incremental supply needed in its control area *up to* market capacity margin of the non-domestic market. That is, EO's planner would buy a quantity $Q = Min(l_{EO} - k_{EO}, k_{CM} - l_{CM} - \epsilon)$, acting *de facto* as a monopolist on the quantity to be procured, which ensures he procures imports at marginal cost c when the neighbor has some spare capacity. In this setting, if the planner resells at market prices on its own market, market EO would recover all the cross-border rent CM was extracting from EO and capacity in both markets would recover their optimal level. This way, EO still endures increased curtailment due to unilateral implementation of a neighboring CM, but enjoys decreased system costs. CM's welfare would be same as in the isolated case W^i_{CM}. 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 reducing import capacity. However, only the (unlikely) "curtail all imports" paradigms allows to recover the energy-only's Security of Supply level without implementing an explicit CRM on its own.*

Proof. Follows from previous developments ■

OA.8 A capacity market that increases net surplus of neighbors – general case

We saw in Section 4 and Appendix C that when the capacity target was not too high (i.e. no more than twice the equilibrium capacity), net surplus in CM increased, at the expense of EO's Security of Supply. However, if the target in CM is so high that operational capacity in EO falls to 0, and EO's SoS target is low enough, such an integration can increase net surplus in the EO market.

Assume the resulting SoS in the energy-only market does not infringe EO's minimum SoS criteria:

$$\bar{\mathcal{L}}_{EO} \geq \mathcal{L}_{EO}(\bar{k}, 0) = \iint_{l_{CM} \geq \bar{k}} l_{EO} f(l) dl + \iint_{\substack{l_{CM} \leq \bar{k} \\ l_{CM} + l_{EO} > k^T}} (l_{CM} + l_{EO} - k^T)) f(l) dl$$

This pins down the minimum target $\bar{k}$ at which CM'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, net surplus in EO is :

CM has no CRM yet:

$$\begin{aligned} W_{EO}(k_{CM}, K^{eq} - k_{CM}) =& (\bar{P} - c) \iint_{l_{CM} + l_{EO} \leq K^{eq}} l_{EO} f(l) dl \\ \mathcal{L}_{EO} =& \mathcal{L}_{EO}(\alpha K^{eq}, (1 - \alpha) K^{eq}) \end{aligned}$$

CM has a CRM:

$$\begin{aligned} W_{EO}(\bar{k}, 0) =& (\bar{P} - c) \iint_{l_{CM} + l_{EO} \leq \bar{k}} l_{EO} f(l) dl \\ \mathcal{L}_{EO} =& \mathcal{L}_{EO}(\bar{k}, 0) \end{aligned}$$

If $\bar{k} > K^{eq}$ and EO meets its SoS target, CM's CRM improves EO's net surplus.

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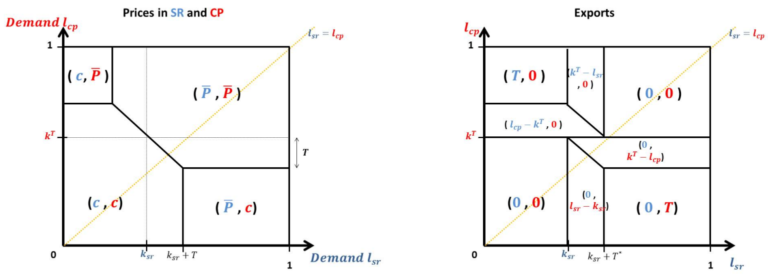

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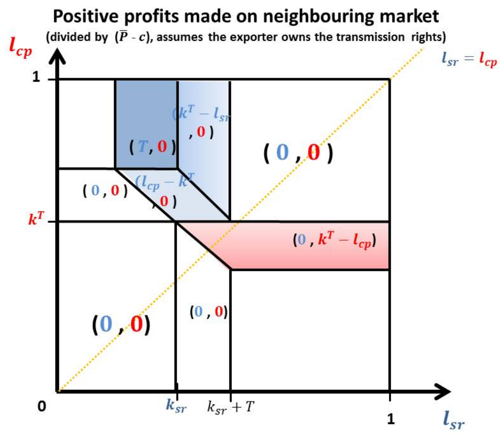


(b)

Figure 1: Prices in market SR and CM (top left), Exports (top right) and profits made abroad (bottom) as a function of demand l_{SR} and l_{CM}. Red (blue) areas indicate money transfers from SR to CM (CM to SR).

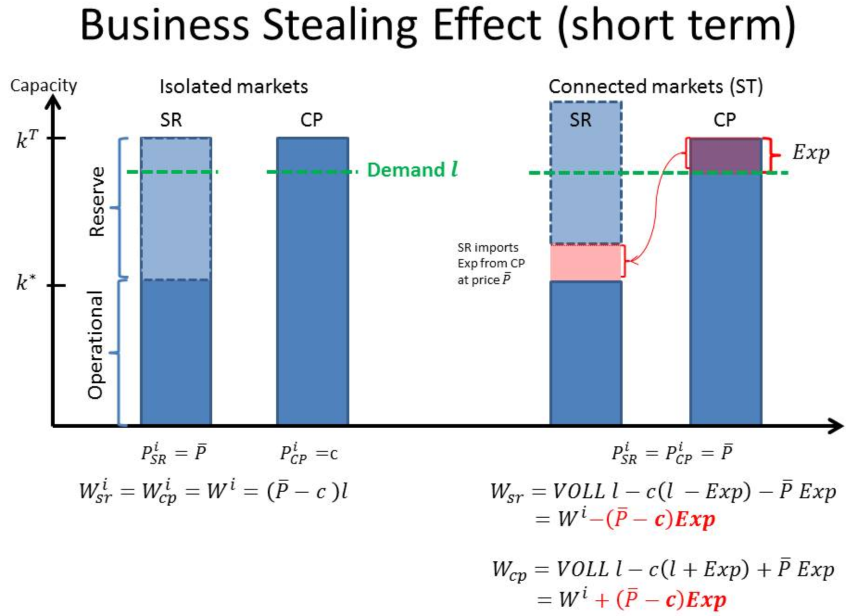
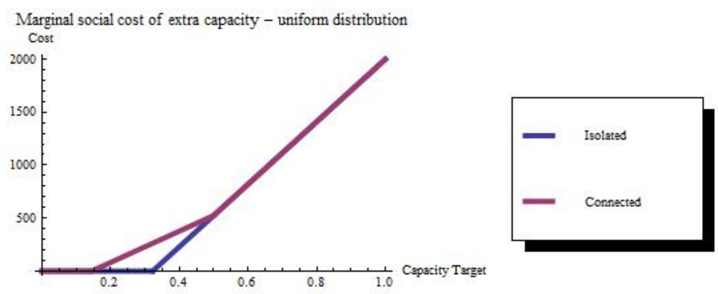


Figure 2: Cross subsidization of CM's capacity market scheme by SR (strategic reserve)



(a)

Figure 4: Marginal social cost of extra strategic reserve in SR (connected with EO), when demand follows a uniform distribution on $[0, 1]$.
$r = 2000$, $\bar{P} = 3000$, $c = 50$, $k_{CM} = 0.5$

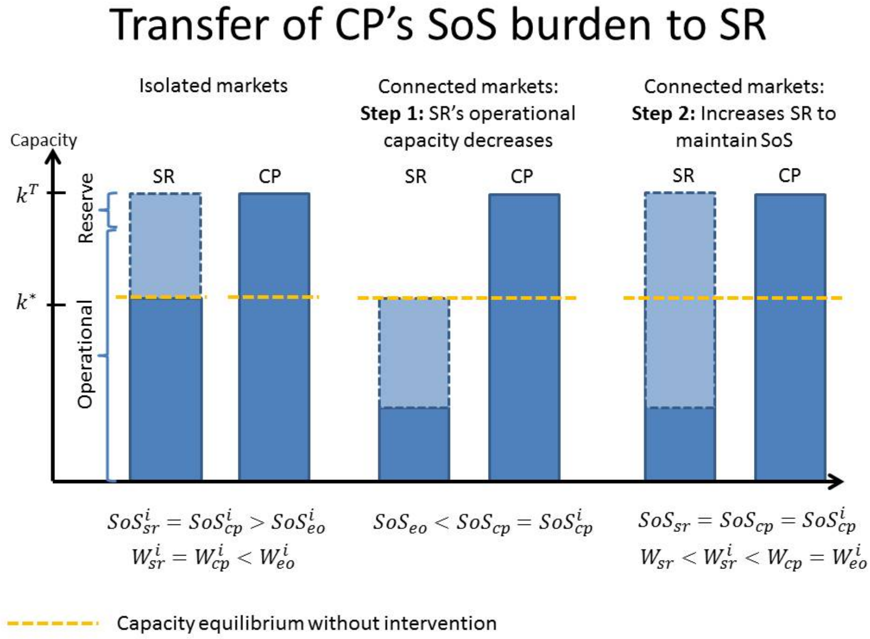
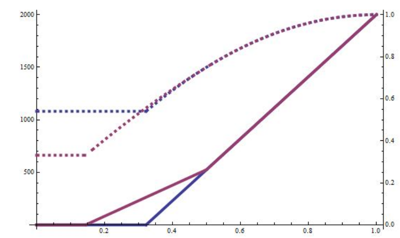
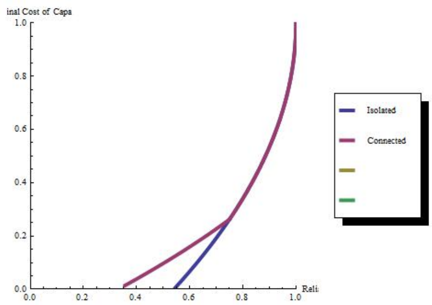


Figure 3: In the long run, SR will bear the cost of CM's capacity market scheme



(a)



(b)

Figure 5: 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 CM market.
Bottom: Marginal cost of the last unit of capacity, as a function of demand coverage Uniform distribution, Blue=Isolated, Purple=Connected $r = 2000, \bar{P} = 3000, c = 50$, $k_{CM} = 0.5$