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“Decentralised Cross-Border Interconnection”

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Decentralised Cross-Border Interconnection

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Abstract

Reaping the full benefits from cross-border interconnection typically requires reinforcement of national networks. When the relevant parts of the networks are complements, a lack of coordination between national transmission system operators typically results in investment below optimal levels in both interconnectors and national infrastructure. A subsidy to financially sustain interconnector building is not sufficient to restore optimality; indeed, even when possible, such subsidisation may have to be restrained so as not to encourage cross-border capacities that will not be fully utilised due to lack of investment in national systems.

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1 Introduction

In Europe, as well as in most other parts of the world, cross-border interconnection is typically based on bilateral agreements between the operators of the systems linked by the interconnector. While such agreements may cover both the design of the interconnector and the sharing of its costs, they generally do not extend to the reinforcements in domestic transmission systems that would be warranted to achieve

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the full benefits of interconnection. As a result, such projects tend to be suboptimal, or they are not undertaken at all.

An example from France and Spain may illustrate the difficulties. In 2008, the electricity transmission and system operators of France and Spain, Réseau de Transport d'Electricité (RTE) and Red Eléctrica de España (REE), created Inelfe, a corporation jointly-owned in equal shares, with the aim of constructing a new electrical interconnection through the Eastern Pyrénées that would effectively double the exchange capacity from 1,400 MW to 2,800 MW.[1] In a report published by the French regulator in November 2015,[2] shortly after the line was inaugurated, it appeared that the commercial capacity effectively made available to the market could not reach the level initially expected:

> 'In the Spain-to-France direction, the delay in the installation of a phase-shifting transformer in Spain limits capacity that can be allocated to the market to 2,300 MW. This equipment is set to be put into operation in 2017. Moreover, the interconnection capacity effectively available in both directions is currently limited by constraints in the Spanish domestic network. In particular, due to problems with local acceptance, the construction of two separate lines downstream of the new link did not go as scheduled, with a portion of the route finally being built with one line only. As a consequence, this part of the route is the cause of stricter capacity limits, in compliance with Spanish operating rules. Interconnection capacity between France and Spain is therefore limited to an average of 2,000 MW in both directions, for the greater part of the year 2016.'

As a result, the benefits of the interconnection were reduced.[3]

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[1] http://www.inelfe.eu/IMG/pdf/Spain_France_electrical_interconnection_ENG-compressed.pdf. Ciupuliga and Cuppen (2013) details the long story of this interconnector.

[2] Deliberation by the French Energy Regulatory Commission of 26 November 2015 containing its opinion on the structure for allocation of capacity between timeframes at the border between France and Spain, following the commissioning of a new interconnection between the two countries: http://www.cre.fr/en/documents/deliberations/avis/france-spain-electricity-interconnection/read-deliberation.

[3] The Inelfe electrical interconnector has some similarities with the Midi-Catalogne (Midcat) project to connect France and Spain with a gas pipe (cf. http://www.platts.com/latest-news/natural-gas/london/analysis-traders-skeptical-on-french-spanish-26240144). The project, meant to increase supply to Western Europe from different sources in Spain, including imports from Algeria, required France to reinforce its domestic network; out of a total cost of 3.1 billion euros 2.3 billion euros would have to be spent in France. In 2016, the European Commission funded two engineering studies to develop Midcat, and contracts were signed with Enagas and TIGF, the Spanish and French gas transmission system operators. Funding would come from the Connecting Europe Facility, the Commission's programme to finance energy infrastructure, and would have covered up

The difficulties arising from decentralised decision-making in an integrated network have not gone unnoticed. In Europe, the Agency for Cooperation of Energy Regulators (ACER) was set up in 2010 as an Agency of the European Union by the Third Energy Package to further the completion of the internal energy market both for electricity and natural gas (European Council, 2009a); its aims include 'an efficient energy infrastructure guaranteeing the free movement of energy across borders and the transportation of new energy sources, thus enhancing security of supply for EU businesses and consumers' (www.acer.europa.eu). European transmission system operators cooperate in the European Network for Transmission Operators for Electricity (ENTSO-E) and European Network for Transmission Operators for Gas (ENTSO-G); among their tasks is to produce Ten-Year Network Development Plans (TYNDPs) to provide a consistent view of the pan-European infrastructure and signal potential gaps in future investment – these plans form the basis for the European Commission's selection of so-called Projects of Common Interest. In the 2016 Winter Package (European Commission, 2016), the European Commission foresaw the establishment of regional entities which would take over functions and responsibilities from national transmission system operators.[4] Nevertheless, even though much has happend to coordinate decisions on energy infrastructure in Europe, it is still the case that, within their jurisdictions, national regulators and system operators have discretion.[5]

From a purely technical point of view, building a new line between two network nodes causes costs and benefits that do not depend on in which jurisdiction nodes are located. The basic economic models of electricity transmission developed for building and operating domestic lines may therefore be applied to the study of interconnectors.[6] Interconnectors generate revenue based on price arbitrage between nodes. If the price differential between two nodes is sufficiently large, the discounted revenue stream is larger than the cost of building and operating a connecting line,

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to 50 percent of costs. Nevertheless, the project was cancelled in 2019 after being blocked by both the French and the Spanish regulators (https://www.cre.fr/content/download/20284/258733). Given recent events in Ukraine, it could conceivably be resurrected in an effort to reduce Europe's dependence on Russian gas.

[4] Regionalisation of the electricity sector was analysed in Crampes, von der Fehr and Steel (2017); see also Bohne (2011) and Kolk (2014).

[5] Even at the ENTSO-E level, things are not crystal clear. For example, in Opinion n° 03/2021 of the European Union Agency for the Cooperation of Energy Regulators of 3 May 2021 on the methodological aspects of the ENTSO-E draft Ten-Year Network Development Plan 2020, ACER criticises the 2020 TYNDP for some remaining uncertainty *"regarding the estimation of the project costs in the case of non-mature projects, and in which cases the indicated costs include the assumed costs of reinforcement of internal networks that would be necessary for the cross border capacity increases."* ENTSO-E published a revised version in August 2021.

[6] See for example Joskow and Tirole (2000).

and private investors would be willing to bid for the right to install a new link between these nodes. However, when the two nodes are in different jurisdictions, they are typically subject to different sets of rules and controlled by decision-makers with potentially divergent interests. It is this heterogeneity that makes the economics of interconnectors different. For example, depending on whether markets on the two sides of a border are coupled or related through a system of coordinated auctions, the way to manage cross-border trade may be different, and so is the (private) value of an electric link.[7] The prospects and problems of transmission investment also vary depending on whether it is purely merchant or under tight regulation.[8] Similarly, the organization and regulation of the markets at the two ends of the line have an effect on the incentives to reduce congestion costs.[9]

In the literature on the economics of energy markets, there is a variety of works related to interconnectors. Keppler and Meunier (2018) use cost-benefit analysis to determine the socially optimal increase in interconnection capacity. Hoffler and Wittmann (2007) investigate capacity auctioning. Newbery and Grubb (2015) defend the idea that the contribution from interconnectors should be included to determine the amount to procure in capacity mechanisms and Hagspiel et al (2018) consider the role of interconnectors for reliability assessments. Turvey (2006) explains why the utilisation of some interconnectors is sub-optimal. Debia et al. (2018) and Massol and Banal-Estañol (2018) analyse the impact of market power on the use of electric and gas interconnectors. On the regulation side, Mountain and Carstairs (2018) explain why self-assessed proposals by transmission companies for interconnector development do not provide appropriate incentives. None of these papers explicitly takes externalities from domestic investment and the related regulatory issues into consideration.

The issue is addressed in some case studies. In de Jong et al. (2007), one finds

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[7] See Brunekreeft et al. (2005). The paper is part of a special issue of Utilities Policy (vol 13, issue 2 - June 2005) fully dedicated to electricity transmission.

[8] *"Having different national regimes on each side of the interconnector, fully regulated and merchant, may result in asymmetric interests for the investors involved in the interconnector project, as the parties involved may not face similar construction and operational incentives. There is a clear need for a co-ordinated approach, which may not be identical in each case, but must be consistent and coherent. It is important for National Regulatory Authorities (NRAs) to be able to reach a common position and to set out a clear and predictable framework within which investment can be made."* Ofgem (2013).

[9] Extract from CRE's Public consultation n°2021-07 of 17 June 2021 relating to the GridLink interconnection project and to the opportunity of a new interconnector between France and the United-Kingdom, page 9: *"In the best-case scenario, where the United Kingdom remained in the internal energy market, but where Brexit had an impact on electricity demand and the development of renewable energy capacities, the value of a new interconnector could fall by up to 10%. In the case of decoupled electricity markets, the value of a new interconnector could fall by more than 30%."*

three case studies of European interconnector investment: NorNed (between Norway and The Netherlands), Estlink (between Estonia and Finland) and BritNed (between United Kingdom and The Netherlands). The authors describe the regulatory assessments of the three interconnector projects. At that time, ACER did not exist so that only pairs of national regulators were involved. Crampes and Rives (2011) analyse the hierarchical regulatory structure created by the Third Energy Package through a study of the powers attributed to each actor and a modeling of the actors' relationships.[10] Both national and European regulators scrutinize transmission system operators' activities and each organization has powers that affect the transmission system operators' decisions on interconnection. The main conclusion of Crampes and Rives is that it is always optimal to decentralise part or all of the provision of incentive policies. The authors also consider the possibility of mergers between national transmission system operators and the subsequent likely development of international transmission system operators with stakes in several countries under separated regulation mechanisms, discussing how the regulatory structure should evolve and how the relationships between an international transmission system operator and its regulator(s) could be altered.[11]

In this paper, we abstract from many technical and institutional details considered in previous studies and concentrate instead on the interaction between cross-border interconnectors and national infrastructure, a topic that has so far received relatively little attention in the literature on networks and interconnectors. We demonstrate that such interaction inevitably creates inefficiencies, even when the countries involved are able to reach an efficient agreement on interconnection; so long as investments in national infrastructure are not coordinated, neither interconnector capacity nor domestic capacities are optimal. For this reason support to interconnectors – along the lines currently being followed in Europe – cannot restore optimality; indeed, under reasonable assumptions such support should be restricted, in order not to encourage the building of interconnectors that will not be efficiently utilised.

Our analysis is closely related to the literature on local provision of public goods, starting with Williams (1966).[12] A recent contribution to this literature is Bloch and Zenginobuz (2007), who consider the impact of spillovers on the supply of public goods in a non-cooperative game between different governments in which spillovers

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[10] It is based on an analytical framework designed by Caillaud, Jullien and Picard (1996).

[11] Castaneda et al. (2015) use empirical studies from behavioral economics and psychology to show that systems with independent regulatory agencies weaken the effects of political power, and diminish information asymmetries which improves sector performance.

[12] Other early contributions include Brainard and Dolbear (1967) and Boskin (1973).

may be symmetric or asymmetric and jurisdictions may differ in size; they conclude that the complexity of interactions will plague the design of institutions for multi-jurisdictional local public good economies with spillovers. A distinguishing feature of our model is that we assume that governments may be able to reach an efficient solution for the public good itself (the interconnector), but that overall optimality is not achieved because of the interaction (spillovers) between local networks and the interconnector. We point out that this result implies that moving the decision on the interconnector to a supranational level does not solve the problem, unless that authority can also control national investments (either directly, or indirectly through financial transfers). We also consider the possibility that the public good (interconnector) is provided by a third party (merchant line) and that national transmission operators have ownership interests across borders.

The rest of the paper is organised as follows. In Section 2 we build a model to analyse the optimal size of two domestic networks and a line connecting them, and we show that, if the two countries only cooperate in the design of the interconnector and independently choose their national networks, all investment will be suboptimal when there are positive externalities. In Section 3, we show that a subsidy aimed at the interconnector has positive effects on the size of the interconnector, but does not allow for reaching the optimal size in both domestic and cross-border capacities; an additional subsidy for the reinforcement of national lines is required. Finally in Section 4 we consider some extensions of the model to the case of merchant investments, international TSOs and independant TSOs. Section 5 concludes.

2 A formal analysis

To better understand the basic economic problem created by interrelations between interconnectors and national networks, and to discuss possible policy interventions, in this section we develop a simple model with two countries that partially cooperate in the installation of an interconnector linking their respective networks. After a presentation of the assumptions of the model, we determine optimal investment in interconnection and domestic capacities. We then consider investments when countries independently decide on domestic capacities while the interconnector is jointly designed and financed. In the next section, we analyse policy interventions.

2.1 The model

Two neighbouring countries, indicated by upper- and lower-case letters respectively, receive gross surpluses of $S(\kappa, K, k)$ and $s(\kappa, K, k)$, depending on the capacity of the interconnector κ and the (additional) domestic capacity of (or investment in) their own networks K and k. Capacity and investments are measured in monetary terms.

We assume that the surplus of each country is strictly increasing in both interconnector and domestic capacity; that is, S_κ, s_κ, S_K, $s_k > 0$, where subscripts indicate partial derivatives with respect to the indicated variable.

We further assume that surpluses are weakly increasing in the capacity of the neighbouring country, that is $S_k \geq 0$ and $s_K \geq 0$, implying a non-negative externality from domestic investment on the neighbouring country. This would be the case if, as in the Inelfe and Midcat examples, the transmission lines making up the interconnector and domestic capacities are part of the same chain through which energy will flow from one country to the other; then, when domestic capacity is effectively limiting cross-border flows, domestic investment would increase flows and hence benefit the neighbouring country.[13] It is conceivable, if K and/or k represent parts of the domestic grids located out of the chain that feeds the interconnector, that cross-border flows create loop-flows resulting in negative externalities, but we do not consider this possibility here (the analysis would essentially be the same, albeit with a tendency to over- rather than under-investment).

We would generally expect that capacities are marginal complements, i.e. $S_{ij} > 0$ and $s_{ij} > 0$, where $i, j = \kappa, K, k$ and $i \neq j$. Specifically, in our context it seems reasonable that investment in domestic infrastructure increases the marginal gain from the interconnector, or, at the very least, does not reduce it; hence we assume $S_{\kappa K}, S_{\kappa k}, s_{\kappa k}, s_{\kappa K} \geq 0$. It is less clear what to expect about the relationship between domestic capacities, i.e. the sign of S_{kK} and s_{kK}. While we concentrate attention on the case of marginal complements below, i.e. $S_{kK}, s_{kK} > 0$, we also consider the case of substitutes, i.e. $S_{kK}, s_{kK} < 0$.

Finally, in order to guarantee that second-order conditions are satisfied, we assume that gross surpluses are strictly concave. The explicit expressions for concavity conditions are given in the Appendix.

Example. For illustration and concreteness, we will sometimes consider a case with symmetric specification of the surplus functions:

$$S(\kappa, K, k) = s(\kappa, K, k) = 2\left(\kappa K k\right)^{\frac{1}{4}}. \tag{1}$$

This Cobb-Douglas-like specification has properties lying between complete sub-

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[13] A simple modelling of this setting is as follows: Let $U(q)$ be the gross surplus derived in a country from the transit of energy q into the country and let K, κ and k be the respective capacities of the successive links in the chain. Then we have $q = \min\{k, \kappa, K\}$ so that $S(\kappa, k, K) = U(\min\{k, \kappa, K\})$. If k is the weakest (smallest) link in the chain, i.e $k = \min\{k, \kappa, K\}$, it is clear that $S_k = U'(k) > 0$. Otherwise, $U(\min\{k, \kappa, K\})$ does not depend on k, so that $S_k = 0$.

stitutability, i.e. $S(\kappa, K, k) = s(\kappa, K, k) = U(\kappa + K + k)$, and complete complementarity, i.e. $S(\kappa, K, k) = s(\kappa, K, k) = u(\min\{\kappa, K, k\})$, for some concave functions U and u. There are positive externalities, i.e. $S_k = \frac{1}{2}\left(\frac{\kappa K}{k^3}\right)^{\frac{1}{4}} > 0$ and $s_K = \frac{1}{2}\left(\frac{\kappa k}{K^3}\right)^{\frac{1}{4}} > 0$; surplus functions are concave, in particular, $S_{KK} = -\frac{3}{8}\left(\frac{\kappa k}{K^7}\right)^{\frac{1}{4}} < 0$ and $s_{kk} = -\frac{3}{8}\left(\frac{\kappa K}{k^7}\right)^{\frac{1}{4}} < 0$; and capacities are marginal complements, i.e. $S_{K\kappa} = s_{K\kappa} = \frac{1}{8}\left(\frac{k}{\kappa^3 K^3}\right)^{\frac{1}{4}} > 0$, $S_{k\kappa} = s_{k\kappa} = \frac{1}{8}\left(\frac{K}{\kappa^3 k^3}\right)^{\frac{1}{4}} > 0$ and $S_{Kk} = s_{kK} = \frac{1}{8}\left(\frac{\kappa}{K^3 k^3}\right)^{\frac{1}{4}} > 0$.

2.2 Optimal investment

Net surpluses in the two countries are given by

$$W(\kappa, K, k) = S(\kappa, K, k) - K - \theta\kappa, \tag{2}$$

$$w(\kappa, K, k) = s(\kappa, K, k) - k - (1-\theta)\,\kappa, \tag{3}$$

where θ and $1-\theta$ are the respective shares of interconnector costs born by the two countries.

Maximisation of the sum of net surpluses,

$$\Omega(\kappa, K, k) \overset{\text{def}}{=} W(\kappa, K, k) + w(\kappa, K, k), \tag{4}$$

leads to the following first-order conditions:

$$S_\kappa + s_\kappa = S_K + s_K = S_k + s_k = 1. \tag{5}$$

Since S_κ and s_κ are both positive the interconnector is a public good. If, in addition, there are positive externalities, i.e. $S_k > 0$ and $s_K > 0$, the marginal benefit from domestic investment must include the spillover effects on the surplus of the neighbouring jurisdiction. Therefore, optimality requires that the sum of marginal gross surpluses across countries equals marginal cost, where the latter is normalised to 1 for each type of investment.

We denote the solution to (5) by $\{\kappa^*, K^*, k^*\}$.

Example. In the Cobb-Douglas specification, the sum of net surpluses becomes

$$\Omega(\kappa, K, k) = 4(\kappa K k)^{\frac{1}{4}} - K - k - \kappa. \tag{6}$$

From the optimality conditions (5), we find that the optimal solution is

$$\kappa^* = K^* = k^* = 1, \tag{7}$$

with the maximum value of the sum of net surpluses being $\Omega^* = 1$.

2.3 Partial cooperation

We now consider the following equilibrium: i) each country decides, independently and simultaneously, on the capacity of its own network; and ii) at the same time the two countries negotiate an agreement on the capacity of the interconnector and the sharing of the associated costs.

Negotiation is modeled by the Nash Bargaining Solution, where we assume that both countries have a reservation value equal to zero:

$$\max_{\kappa,\theta} W^{\alpha} w^{1-\alpha}, \tag{8}$$

where α and $1-\alpha$ indicate the respective bargaining power of the two countries.

Note that domestic capacities K and k are not in the list of joint decisions in (8). Indeed, we assume that capacities of domestic networks are non-contractible. As explained in Section 1 above, this may be a result of institutional or legal constraints. However, non-contractability could also be for informational reasons (non-observability or non-verifiability). Of course, if domestic capacities were contractible and included in negotiations, total surplus would be maximised.

Differentiating the function $W^{\alpha} w^{1-\alpha}$ with respect to the cost-sharing rule, θ, and equating the derivative to zero, we get

$$\frac{W}{w} = \frac{\alpha}{1-\alpha}. \tag{9}$$

In other words, the sharing rule is such that the ratio of the two countries' net surpluses is proportional to the ratio of their bargaining powers. If $\alpha \to 1$ (repectively 0), W (resp. w) is maximized and w (resp. W) is zero. When the two countries have the same bargaining power, they obtain the same net surplus, i.e. $W = w$.

The first-order condition for the capacity of the interconnector may be written

$$\alpha w \left(S_{\kappa} - \theta\right) + \left(1-\alpha\right) W \left(s_{\kappa} - (1-\theta)\right) = 0. \tag{10}$$

Using (9), (10) reduces to

$$S_{\kappa} + s_{\kappa} = 1. \tag{11}$$

The condition on interconnector capacity (11) is the same as obtained when maximising the sum of net surpluses, given in (5). Even though the two countries have conflicting interests with respect to surplus sharing, as long as they both have positive barganing power, i.e. $0 < \alpha < 1$, they have a common interest in choosing an interconnector that maximises total surplus.

The common interest does not extend to domestic capacities. For the non-cooperative part of the game, we consider the Nash equilibrium. In other words, the two countries solve, respectively,

$$\max_{K} W, \tag{12}$$

$$\max_{k} w, \tag{13}$$

leading to the first-order conditions

$$S_K = s_k = 1. \tag{14}$$

We denote the solution to (11) and (14) by $\left\{\kappa^b, K^b, k^b\right\}$.

Comparing (11) and (14) with (5), it follows that, absent any domestic externality, i.e. if capacity in a neighbouring country does not directly affect gross domestic surplus, total net surplus is maximised at equilibrium.

Proposition 1. *If* $S_k \equiv 0$ *and* $s_K \equiv 0$, $\left\{\kappa^b, K^b, k^b\right\} = \{\kappa^*, K^*, k^*\}$.

This result does not hold when there are positive externalities, i.e. $S_k > 0$ and/or $s_K > 0$. For example, when $S_{Kk} > 0$ and $s_{kK} > 0$, each country is more inclined to invest in its domestic network the more the other country invests in its own. As domestic investments are not part of the bargaining process, both countries will tend to invest below the optimal level and the interconnector will also be undersized if it is a marginal complement to internal lines.

More specificially, we have:[14]

Proposition 2. *Assume* $S_k > 0$ *or* $s_K > 0$ *and let* $\Omega^\Gamma \overset{def}{=} S + \gamma s - K$ *and* $\Omega^\gamma \overset{def}{=} s + \gamma S - k$. *Then, for all* $\gamma \in [0, 1]$,

$$s_K\left(\Omega_{\kappa K}\Omega^{\gamma}_{kk} - \Omega_{\kappa k}\Omega^{\gamma}_{kK}\right) + S_k\left(\Omega_{\kappa k}\Omega^{\Gamma}_{KK} - \Omega_{\kappa K}\Omega^{\Gamma}_{Kk}\right) < 0 \quad \Rightarrow \quad \kappa^b < \kappa^*, \tag{15}$$

$$-s_K\left(\Omega_{\kappa\kappa}\Omega^{\gamma}_{kk} - \Omega_{\kappa k}\Omega^{\gamma}_{k\kappa}\right) + S_k\left(\Omega_{\kappa\kappa}\Omega^{\Gamma}_{Kk} - \Omega_{\kappa k}\Omega^{\Gamma}_{K\kappa}\right) < 0 \quad \Rightarrow \quad K^b < K^*, \tag{16}$$

$$-S_k\left(\Omega_{\kappa\kappa}\Omega^{\Gamma}_{KK} - \Omega_{\kappa K}\Omega^{\Gamma}_{K\kappa}\right) + s_K\left(\Omega_{\kappa\kappa}\Omega^{\gamma}_{kK} - \Omega_{\kappa K}\Omega^{\gamma}_{k\kappa}\right) < 0 \quad \Rightarrow \quad k^b < k^*. \tag{17}$$

Proof. The full proof is in the Appendix, and here we just provide a sketch. Consider the modified surplus functions Ω^Γ and Ω^γ for the two countries respectively, where γ is a parameter measuring the degree of "altruism" in each country. If $\gamma = 0$, we

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[14] This and the following result may be seen as special cases of the more general proposition that Nash equilibria are not welfare optimal, cf. Maskin (1999).

are in the case of pure national concern and maximisation of the weighted sum of surpluses leads to (11) and (14). If $\gamma = 1$, we are in the case of reciprocal regional concern and we obtain (5). In between, the larger the altruism parameter the closer we are to optimality. Differentiating the first-order conditions with respect to γ, we find conditions to ensure that the interconnector κ and the two domestic capacities K and k are increasing in γ. $\square$

Inspection of (15), (16) and (17) reveals that marginal complementarity between capacities, i.e. S_{Kk}, $S_{K\kappa}$, $S_{\kappa k}$, s_{kK}, $s_{k\kappa}$, $s_{\kappa K} > 0$, is sufficient for $\kappa^b < \kappa^*$, $K^b < K^*$ and $k^b < k^*$. However, the result holds more generally. Specifically, since (by second-order conditions) $\Omega_{\kappa\kappa}\Omega^{\gamma}_{kk} - \Omega_{\kappa k}\Omega^{\gamma}_{k\kappa} > 0$ and $\Omega_{\kappa\kappa}\Omega^{\Gamma}_{KK} - \Omega_{\kappa K}\Omega^{\Gamma}_{K\kappa} > 0$, $K^b < K^*$ and $k^b < k^*$ if $\Omega_{\kappa\kappa}\Omega^{\Gamma}_{Kk} - \Omega_{\kappa k}\Omega^{\Gamma}_{K\kappa}$ and $\Omega_{\kappa\kappa}\Omega^{\gamma}_{kK} - \Omega_{\kappa K}\Omega^{\gamma}_{k\kappa}$ are sufficiently small; this may well be true even if some, or all, capacities are substitutes.

Intuitively, one would expect that at equilibrium, since externalities are internalised for the interconnector but not for domestic capacities, interconnector capacity is closer to its optimal value than domestic capacities are to theirs. While clearly not a general result, in the case of symmetric countries we have a simple sufficient condition for the result to hold. Specifically, we have the following:

Proposition 3. *Consider the case of symmetric countries, i.e.* $S(\kappa, K, k) \equiv s(\kappa, k, K)$, *and assume that, for all* $\gamma \in [0,1]$, $(\Omega_{\kappa\kappa} + 2\Omega_{\kappa k})(\Omega^{\gamma}_{kk} - \Omega^{\gamma}_{kK}) > 0$. *Then* $K^* - K^b = k^* - k^b > \kappa^* - \kappa^b$.

Proof. We use the same method as in the proof of Proposition 2, finding sufficient conditions for K and k to increase faster than κ with γ. $\square$

We note that the result holds as long as interconnector and domestic capacities are not strong complements, i.e. $\Omega_{\kappa k} = \Omega_{\kappa K} < -\frac{1}{2}\Omega_{\kappa\kappa}$, and, at the same time, domestic capacities are not strong substitutes, i.e. $\Omega^{\gamma}_{kK} > \Omega^{\gamma}_{kk}$.

Example. The above results hold in our Cobb-Douglas specification. The equilibrium conditions with partial cooperation (11) and (14) imply

$$\kappa^b = \frac{1}{4},\ K^b = k^b = \frac{1}{8}, \tag{18}$$

with the value of the sum of net surpluses now being $\Omega^b = \frac{1}{2}$. Comparing the equilibrium outcome with optimal investment, i.e. $\kappa^* = K^* = k^* = 1$, we find two types of distortions: not only are all types of capacities inefficiently small, but they also differ in size; specifically, domestic capacities are smaller than the interconnector capacity and hence further away from their optimal values.

3 Policy Analysis

To restore optimality, one needs the power to intervene in the decision process, for example by providing financial support for investments that create positive externalities. The European Commission offers subsidies or loans at reduced rates to selected interconnectors.[15] Below we show that even though such financial aid has positive effects on the size of the interconnector, it does not allow for reaching the optimal size in both domestic and cross-border capacities. We then demonstrate that subsidies reflecting the externalities of domestic capacities provide incentives to invest efficiently; however, such a scheme would meet with both regulatory and political difficulties.

3.1 Interconnector subsidies

Suppose that investment in interconnection capacity is subsidised at rate σ, where $\sigma = 0$ corresponds to no subsidy and $\sigma = 1$ corresponds to full coverage of cost. Then the relevant equilibrium condition corresponding to (11) becomes

$$S_\kappa + s_\kappa = 1 - \sigma, \tag{19}$$

whereas (14) remains unchanged.

Differentiating the system made up of (14) and (19) with respect to σ, and recalling that $\Omega = S + s - \kappa - K - k$, we obtain

$$\begin{bmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ s_{k\kappa} & s_{kK} & s_{kk} \end{bmatrix} \begin{bmatrix} d\kappa \\ dK \\ dk \end{bmatrix} = \begin{bmatrix} -d\sigma \\ 0 \\ 0 \end{bmatrix}. \tag{20}$$

We assume that the equilibrium satisfies the standard regularity conditions, in particular that the matrix on the left-hand side is negative definite, from which it follows that

$$\Delta = - \begin{vmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ s_{k\kappa} & s_{kK} & s_{kk} \end{vmatrix} > 0. \tag{21}$$

We can then establish that an increase in the subsidy increases the size of the interconnector:

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[15] The Inelfe project received a financial grant of 225 million euros under the framework of the European Energy Programme for Recovery (EEPR). Additionally, it received funding from the European Investment Bank through a loan of 350 million euros granted to REE and RTE.

$$\frac{d\kappa}{d\sigma} = \frac{1}{\Delta}\left[S_{KK}s_{kk} - s_{kK}S_{Kk}\right] > 0, \tag{22}$$

since $S_{KK}s_{kk} - s_{kK}S_{Kk} > 0$ from second-order equilibrium conditions.

Furthermore, marginal complementary of infrastructure, i.e. $S_{K\kappa}, s_{k\kappa}, S_{Kk}, s_{kK} \geq 0$, is sufficient for domestic capacities to be increasing in the subsidy also:

$$\frac{dK}{d\sigma} = -\frac{1}{\Delta}\left[s_{kk}S_{K\kappa} - s_{k\kappa}S_{Kk}\right] > 0 \tag{23}$$

$$\frac{dk}{d\sigma} = -\frac{1}{\Delta}\left[S_{KK}s_{k\kappa} - S_{K\kappa}s_{kK}\right] > 0 \tag{24}$$

Under these conditions, a (small) subsidy increases total net surplus; in particular, from the Envelope Theorem we have

$$\frac{d\Omega}{d\sigma}_{\sigma=0} = S_k\frac{dk}{d\sigma} + s_K\frac{dK}{d\sigma} > 0. \tag{25}$$

From these results, it would seem that a subsidy to the interconnector is a policy tool with a high level of efficacy. However, a single tool cannot implement $\{\kappa^*, K^*, k^*\}$, except in the trivial case when there are no externalities, i.e. $S_k = s_K = 0$, in which case $\sigma = 0$ leads to maximisation of total surplus. Indeed, $\sigma > 0$ distorts the first-order condition (19) to push up κ^b, but it does not change the shape of conditions (14) relating to domestic capacities. In other words, this type of direct subsidisation is inefficient because it does not correct for the lack of internalisation of external effects. We conclude that

Proposition 4. *Subsidising the interconnector is welfare improving (for sufficiently low levels of the subsidy), but not sufficient to implement optimal investment.*

Intuitively, one would expect that the (direct) effect of the subsidy on the interconnector is stronger than the (indirect) effects on domestic capacities. Comparing (22) with (23) and (24), respectively, we find that a sufficient condition for this to be true is that complementarities are not too strong:

Proposition 5. *Suppose* $-s_{kk}S_{K\kappa} + (s_{kK} + s_{k\kappa})S_{Kk} < S_{KK}s_{kk}$ *and* $-S_{KK}s_{k\kappa} + (S_{Kk} + S_{K\kappa})s_{Kk} < S_{KK}s_{kk}$. *Then* $\frac{d\kappa}{d\sigma} > \frac{dK}{d\sigma}, \frac{dk}{d\sigma}$.

Under the assumptions of Propositions (3) and (5), or, more generally, when both $K^* - K^b$, $k^* - k^b > \kappa^* - \kappa^b > 0$ and $0 < \frac{dK}{d\sigma}, \frac{dk}{d\sigma} < \frac{d\kappa}{d\sigma}$, the subsidy has two different and opposing effects. On the one hand, the subsidy increases all capacities, i.e. $\frac{d\kappa^\sigma}{d\sigma}, \frac{dK^\sigma}{d\sigma}, \frac{dk^\sigma}{d\sigma} > 0$, driving them closer to the optimal levels. On the other hand, the interconnector capacity increases faster than domestic capacities, thereby increasing the relative gap between equilibrium and optimal levels.

Given these observations, we would expect that, with a subsidy that maximises the sum of net surpluses, either all capacities are below optimal levels or only the interconnector capacity exceeds it. In our Cobb-Douglas specification, the former turns out to be true.

Example. We find, from (19) and (14),

$$\kappa^{\sigma} = \frac{1}{4\left(1-\sigma\right)^{2}}, \tag{26}$$

$$K^{\sigma} = k^{\sigma} = \frac{1}{8\left(1-\sigma\right)}. \tag{27}$$

With $\sigma = \frac{1}{2}$ interconnection capacity is at the optimal level, i.e. $\kappa = \kappa^{*} = 1$, while domestic capacities are sub-optimal, i.e. $K = k = \frac{1}{4} < K^{*} = k^{*} = 1$. Conversely, at $\sigma = \frac{7}{8}$ domestic capacities are at the optimal levels, i.e. $K = k = K^{*} = k^{*} = 1$, while the interconnector is super-optimal, i.e. $\kappa = 16 > \kappa^{*} = 1$.

Do these results mean that there is a trade off between interconnector capacity on the one hand and domestic capacities on the other? In other words, should we expect that, with a single policy tool, over-investment in interconnector capacity is required in order to drive domestic capacities sufficiently close to their optimal levels? The answer is no.

To illustrate this point, we may write the sum of net surpluses as a function of the subsidy by inserting (26) and (27) into (6). In the parametrised setting, we obtain

$$\Omega\left(\kappa\left(\sigma\right), K\left(\sigma\right), k\left(\sigma\right)\right) = \frac{3}{4\left(1-\sigma\right)} - \frac{1}{4\left(1-\sigma\right)^{2}}. \tag{28}$$

This function reaches its maximum at $\sigma = \frac{1}{3}$. At this point, $\kappa = \frac{9}{16}$, while $K = k = \frac{3}{16}$. With the interconnector subsidy, all capacities are closer to the optimal values than without the subsidy (where $\kappa^{b} = \frac{1}{4}$ and $K^{b} = k^{b} = \frac{1}{8}$). However, capacities are still well below efficient levels ($\kappa^{*} = K^{*} = k^{*} = 1$).

The reason for these results is the different effects of subsidisation alluded to above. First, subsidising the interconnector increases the absolute level of all investment, i.e. $\frac{d\kappa^{\sigma}}{d\sigma} > 0$ and $\frac{dK^{\sigma}}{d\sigma} = \frac{dk^{\sigma}}{d\sigma} > 0$, which increases efficiency; this is reflected in the first term on the right-hand side of (28), which is increasing in σ over the relevant range. Second, subsidising the interconnector increases the gap between domestic and cross-border investment, in particular $\frac{K^{\sigma}}{\kappa^{\sigma}} = \frac{k^{\sigma}}{\kappa^{\sigma}} = \frac{1-\sigma}{2}$ is decreasing in σ, which reduces efficiency; this is reflected in the last term on the right-hand side of (28), which is decreasing in σ over the relevant range. It turns out that, in this example, the surplus maximising subsidisation policy leaves all capacities inefficiently low.

3.2 Externalities compensation

For completeness, we consider the possibility of rewarding countries for the positive externalities caused by their domestic investments.

Suppose the two countries, instead of solving the problems (12) and (13), solve the following problems,

$$\max_{K} S(\kappa, K, k) - (1+T)\,K - T_0, \tag{29}$$

$$\max_{k} s(\kappa, K, k) - (1+t)\,k - t_0, \tag{30}$$

where $\{T, T_0, t, t_0\}$ is a set of (linear) transfers or contributions.

The first-order conditions for these problems are

$$S_K(\kappa, K, k) = 1 + T, \tag{31}$$

$$s_k(\kappa, K, k) = 1 + t. \tag{32}$$

Clearly, by setting

$$T = -s_K\left(\kappa^*, K^*, k^*\right), \tag{33}$$

$$t = -S_k\left(\kappa^*, K^*, k^*\right), \tag{34}$$

and assuming that interconnector capacity is determined as above by condition (11), we obtain the optimality conditions (5) for all capacities.

In the Appendix, we suggest a mechanism to implement this solution and provide a formal proof of the result. The mechanism is based on the existence of a supranational agency with the power to introduce the warranted regulation, including for optimisation of the size of the interconnector to maximise total surplus and the collection of the necessary contributions. We demonstrate that implementing optimality requires equal treatment of countries (same weight on surpluses) and no constraints on the financing contributions from individual countries.

Matters are different if the financial contributions towards the interconnector are constrained, say by the political acceptability of financing the associated costs. The support to domestic investment is provided in order to generate benefits in the neighbouring country. In the absence of international transfers, this support will have to be financed by raising domestic tariffs (or by some other means of national taxation). Such a tariff burden is likely to meet with resistance, in particular if the costs and benefits are unequally distributed across the two countries. The Midcat project, where investment were required in France in order for Spain to reap benefits, is an example of how such difficulties may preclude cross-border agreement.

In the Appendix, we model this idea by assuming that the contributions must satisfy

$$\begin{aligned} TK + T_0 &\leq F, && (35) \\ tk + t_0 &\leq f. && (36) \end{aligned}$$

We show that when at least one these constraints is binding, the interconnector is undersized. Furthermore, such constraints will tend to distort the variable parts of the contributions, T and t, and hence domestic investments, K and k. Suppose for example that the externality is provoked by one country, justifying a substantial subsidy to its domestic investment. The possiblity for financing such a subsidy might however be limited by the constraint on the contribution from the other country. As a result, the subsidy will be too weak resulting in underinvestment.

Deviations from optimality may also result from unequal treatment of the two countries, perhaps due to asymmetries in the countries ability to influence the supranational agency. Specifically, assume the agency choses interconnector capacity and contributions so as to maximise the weighted sum $\Phi\left(S\left(\kappa, K, k\right) - K\right) + \phi\left(s\left(\kappa, K, k\right) - k\right) - \kappa$, with weights $\Phi \geq \phi$. In the Appendix, we show that such unequal treatment would tend to distort investment towards a larger interconnector, while domestic investments tend to be deficient in the favoured country and excessive in the country that is not favoured. In other words, a country is favoured by the promotion of investment in the interconnetor and the neighbouring domestic network, both of which increases its surplus.

Finally, apart from the difficulty of creating a supranational institution with the power to introduce the relevant regulation, implementation would meet with the standard regulatory problem of asymmetric information; as is evident from (33) and (34), in order to implement optimality the regulator would need to know not only optimal capacites, but also the externalities they cause.

4 Discussion

In this section we consider three variations on the above analysis: first, the interconnector is built by a private company; second, national networks are privately owned; and, third, national network companies have cross-border ownership interests.

4.1 Merchant investment

In the model set up in Section 2, it is implicitly assumed that investment in the interconnector is undertaken under an (efficiently negotiated) agreement between the two countries. While this may often be a reasonable description, especially in Europe, it is not always the case; in particular, investment in interconnectors is sometimes undertaken by third parties. A recent example of such a merchant interconnector is the ElecLink project between France and Great Britain (cf www.eleclink.co.uk).

Typically, the main source of revenue for a merchant interconnector is the congestion rent, i.e. the difference in the price of electricity between the two ends of the interconnector. Under ideal conditions, when price at either end of the interconnector reflects the marginal value of electricity there, incentives for a merchant investor coincides with those of the two countries.[16]

There are, however, many reasons why prices facing merchant investors do not reflect marginal values of electricity, including market failures and regulatory intervention.[17] Such distortions may, in principle, both diminish and enhance incentives to invest. An example of the former is when revenues are tightly regulated[18]; an example of the latter is when the interconnector affects prices in regional markets to the benefit of investors.[19] The recent development of market coupling in Europe has tended to improve investment incentives, by allowing for more efficient use of interconnector capacities.

In any case, for the main concern here – the coordination of international interconnectors with national networks – merchant investment is in itself unlikely to contribute to solving the problem. On the contrary, since there will typically be issues related to the coordination between merchant transmission owners and trans-

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[16] In the setting referred to in Footnote 13, assuming that energy flows from the s to the S country, we would have $S_\kappa + s_\kappa = U'(\kappa) - u'(-\kappa)$ when $\kappa = \min\{k, \kappa, K\}$ and $S_\kappa + s_\kappa = 0$ otherwise. Therefore, if electricity is priced at its marginal value in both countries, i.e. at $U'(q)$ and $u'(-q)$, respectively, at equilibrium we would have $1 = U'(\kappa) - u'(-\kappa) = S_\kappa + s_\kappa$, the same first-order condition as in the original model.

[17] Joskow and Tirole (2005) provide an extensive analysis of how inefficiencies may result from merchant investment, including market power in wholesale electricity markets, lumpiness in transmission investment opportunities, stochastic attributes of transmission networks and associated property rights definition issues, strategic behavior by potential merchant transmission investors and issues related to the coordination of transmission system operators and merchant transmission owners. It may be added that merchant investment can also provide benefits, by more appropriate incentives to invest, to manage costs, to build on time and to make the asset available (Gautier, 2020).

[18] This has been an issue for the Greenlink and NeuConnect projects, interconnectors that will link Great Britain to Ireland and Germany respectively, where Ofgem recently decided to ease the cap and floor regime "to enable project finance solutions" (Ofgem, 2020).

[19] This has been an issue with NorthLink, the proposed interconnector between Great Britain and Norway, that may contribute to higher prices on the Norwegian side to the benefit of power producers involved in the project.

mission system operators (Joskow and Tirole, 2005), merchant investment may well aggravate, rather than ameliorate, coordination problems.

4.2 Independent transmission operators

In the model of Section 2, operators of two separate national networks are supposed to freely chose the level of domestic investment and to freely engage in bilateral negotiations over the capacity of the interconnector. In Section 3, we have considered the possibility of some form of investment regulation by a supranational entity. Given that we are interested in cross-border spillovers, our model is neutral regarding the status of the two national operators. If transmission networks are owned by public companies (like in France and Scandinavia), it is natural to assume that their benefit functions S or s reflects the net national surplus from electricity consumption, that is, the sum of the surplus of electricity consumers and the profit of the operator, as well as the profit of generators connected to the domestic network.

However, if transmission networks are owned by private companies (like in the US), it may be more natural to assume that benefit functions reflect operators' net profits, implying that investments may be undersized and/or delayed because they do not internalise benefits to other market participants. In the case of Inelfe (described in the Introduction), this may be part of the reason why the reinforcement of the Spanish network was delayed. Indeed, the state-owned holding company SEPI has only a minority interest of 20 percent in Red Eléctrica de España, the remainder mainly controlled by foreign institutions.[20] By contrast, on the French side RTE is a wholly owned subsidiary of the French generator Électricité de France, the latter being 85 percent owned by the French state.

An added complexity is introduced when private companies perform both production and transmission.[21] While a regulator may be able to alleviate the a lack of concern for overall national interests, for example by ensuring that third parties can access, or invest in, the network on equal terms,[22] as long as jurisdiction is confined by national borders, it will not solve the problem of inefficient size of interconnectors and cross-border spillovers.

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[20] For details, see https://www.ree.es/en/shareholders-and-investors/share/shareholders-structure

[21] On the regulation of vertically integrated monopolies, see Chapter 11 in Auriol et al. (2021).

[22] A recent example is provided by the Australian Energy Market Commission (AEMC), which in July 2021, issued rules to attract more developers and investors to invest in transmission infrastructure by making it easier to share transmission assets and connection costs, cf. https://www.aemc.gov.au/rule-changes/connection-dedicated-connection-assets.

4.3 International transmission operators

While the interaction between national institutions is generally through cooperation, there are examples of cross-border integration. For example, the Dutch transmission system operator TenneT, since taking over Transpower in 2010, operates a large part of the German grid; the integration meant that a number of interconnectors between the Dutch and the German grids now constitute internal parts of the overall TenneT network.[23]

Cross-border integration may affect both the incentives and the decision-making power of the integrated entity (cf Salop and O'Brien, 2000). Here we concentrate on the former effect, which can easily be accommodated by an extension of the model set out in Section 2. In particular, we now assume that each decision maker puts weight on the net surplus of the neighbouring country:

$$W^{\Delta}(\kappa, K, k) = W(\kappa, K, k) + \Delta w(\kappa, K, k), \tag{37}$$

$$w^{\delta}(\kappa, K, k) = w(\kappa, K, k) + \delta W(\kappa, K, k), \tag{38}$$

where $\delta, \Delta \in [0, 1]$ are the respective weights.

By going through a parallel analysis to that in Section 2.3, we find that the first-order condition for the interconnector reduces to $S_\kappa + s_\kappa = 1$, as before, while the first-order conditions for domestic investments may be written

$$S_K + \Delta s_K = 1, \tag{39}$$

$$s_k + \delta S_k = 1. \tag{40}$$

Clearly, the incentives for domestic investment lies between those with partial cooperation ($\delta = \Delta = 0$) and optimality ($\delta = \Delta = 1$), with distances from the two extremes depending upon how much weight the two countries put on the surplus of its neighbour. By an analysis similar to that underlying Proposition 2, we can find conditions such that closer integration (larger weights Δ and δ) leads to increasing investment (in both interconnector and domestic networks).

We conclude that, by aligning the interests of decision makers, cross-border integration may well ameliorate inefficiencies caused by the public-good nature of interconnectors and the externalities of domestic investments. Further benefits may be achieved if cross-border integration also provides opportunity for directly influenc-

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[23] See https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Gridmaps/DE/G019_21-010_GridMap_V9-D-NL-d.pdf.

ing decisions on the other side of the border. Clearly, such influence is not obvious: while an integrated transmission operator may want to coordinate decisions, they will be subject to national regulation, where national interests will prevail. Integration at both the operational and regulatory level may therefore be warranted to achieve complete coordination.

5 Conclusion

In this paper, we have addressed the relevant scope for decision-making in an international, integrated electricity grid. In many parts of the world, such as in Europe, electricity systems are governed and administered on a national basis even though they are interconnected. While electricity flows freely across borders, national transmission system operators and regulators have discretion regarding domestic infrastructure, and they coordinate only partially with their neighbours on the planning, building and operation of interconnectors.

We have concentrated on one particular aspect of this issue, considering the case when an interconnector is established between two countries that cooperate (perfectly) on its design and sharing of costs, but remain independent with respect to domestic investment. We have shown that because of externalities across borders, investments in both the interconnector and national infrastructure are likely to be suboptimal. A subsidy to financially support interconnector building – a policy currently followed in Europe – is not sufficient to restore optimality; indeed, even when possible such subsidisation may have to be restrained so as not to encourage cross-border capacities that will not be fully utilised due to lack of investment in national systems. Without merging system operators (and maybe even regulatory authorities) into an international entity that would internalise all effects from investments, optimality would require compensations to be paid to each country for externalities created abroad. Such a policy will meet with numerous regulatory and political obstacles, including objections to raising funds for cross-border payments.

While our analysis is based on a simple set up, the insights are not only likely to carry over to more realistic settings, but the problem may even be more serious in such settings. We have assumed that the interconnector is built by the two connecting countries, implying that they internalise the effects of the interconnector on their own systems; if the interconnector were instead built by a third party – often referred to as a 'merchant line' – additional externality issues may arise. Furthermore, a given interconnector cannot be seen in isolation – in some cases it may be an alternative to other projects, in other cases it may complement them

– and hence it may be necessary to take a wider set of interactions into account. Also, grid investments often do not only affect a pair of adjacent countries, but has implications for a wider region (the abandoned Midcat project being one example). Analysis of such cases would require a different framework than ours.

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A Appendix

A.1 Concavity conditions

Strict concavity of the two gross surplus functions means that the matrices

$$\begin{bmatrix} S_{\kappa\kappa} & S_{\kappa K} & S_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ S_{k\kappa} & S_{kK} & S_{kk} \end{bmatrix}, \begin{bmatrix} s_{\kappa\kappa} & s_{\kappa k} & s_{\kappa K} \\ s_{k\kappa} & s_{kk} & s_{kK} \\ s_{K\kappa} & s_{Kk} & s_{KK} \end{bmatrix} \tag{41}$$

are negative definite. In terms of determinants, we have

$$S_{\kappa\kappa} < 0,\ S_{KK} < 0,\ S_{kk} < 0,$$

$$\begin{vmatrix} S_{\kappa\kappa} & S_{\kappa K} \\ S_{K\kappa} & S_{KK} \end{vmatrix} > 0, \begin{vmatrix} S_{KK} & S_{Kk} \\ S_{kK} & S_{kk} \end{vmatrix} > 0, \begin{vmatrix} S_{\kappa\kappa} & S_{\kappa k} \\ S_{k\kappa} & S_{kk} \end{vmatrix} > 0,$$

$$\begin{vmatrix} S_{\kappa\kappa} & S_{\kappa K} & S_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ S_{k\kappa} & S_{kK} & S_{kk} \end{vmatrix} < 0,$$

and similarly for the determinants corresponding to the function $s(\kappa, K, k)$.

Note that these conditions imply decreasing returns to scale in all capacities.

A.2 Characterisation of equilibrium

In this subsection we provide the proofs of Propositions 2 and 3.

Note that, being the sum of concave functions, Ω, Ω^{Γ} and Ω^{γ} are also concave. Both the set of conditions (5) and the set of conditions (11) and (14) may be summarised by

$$\Omega_{\kappa} = \Omega^{\Gamma}_{K} = \Omega^{\gamma}_{k} = 0, \tag{42}$$

where $\gamma = 1$ corresponds to (5) and $\gamma = 0$ corresponds to (11) and (14).

We consider the solution to (42) as a function of γ :

$$\begin{bmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega^{\Gamma}_{K\kappa} & \Omega^{\Gamma}_{KK} & \Omega^{\Gamma}_{Kk} \\ \Omega^{\gamma}_{k\kappa} & \Omega^{\gamma}_{kK} & \Omega^{\gamma}_{kk} \end{bmatrix} \begin{bmatrix} d\kappa \\ dK \\ dk \end{bmatrix} = \begin{bmatrix} 0 \\ -s_K d\gamma \\ -S_k d\gamma \end{bmatrix}. \tag{43}$$

The matrix on the left-hand side of (43) may be written

$$\begin{bmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega^{\Gamma}_{K\kappa} & \Omega^{\Gamma}_{KK} & \Omega^{\Gamma}_{Kk} \\ \Omega^{\gamma}_{k\kappa} & \Omega^{\gamma}_{kK} & \Omega^{\gamma}_{kk} \end{bmatrix} = \begin{bmatrix} S_{\kappa\kappa} & S_{\kappa K} & S_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ \gamma S_{k\kappa} & \gamma S_{kK} & \gamma S_{kk} \end{bmatrix} + \begin{bmatrix} s_{\kappa\kappa} & s_{\kappa K} & s_{\kappa k} \\ \gamma s_{K\kappa} & \gamma s_{KK} & \gamma s_{Kk} \\ s_{k\kappa} & s_{kK} & s_{kk} \end{bmatrix}. \tag{44}$$

Given that the two matrices in (41) are negative definite, it is easily seen that so are the two matrices on the right-hand side of (44). It follows that the matrix on the left-hand side of (44) – being the sum of two negative definite matrices – is negative definite also. The standard second-order conditions for a (stable) equilibrium are therefore satisfied.

From (43), we obtain

$$\frac{d\kappa}{d\gamma} = \frac{1}{\det(A)} \begin{vmatrix} 0 & \Omega_{\kappa K} & \Omega_{\kappa k} \\ -s_K & \Omega^{\Gamma}_{KK} & \Omega^{\Gamma}_{Kk} \\ -S_k & \Omega^{\gamma}_{kK} & \Omega^{\gamma}_{kk} \end{vmatrix}, \tag{45}$$

where

$$\det(A) = \begin{vmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega^{\Gamma}_{K\kappa} & \Omega^{\Gamma}_{KK} & \Omega^{\Gamma}_{Kk} \\ \Omega^{\gamma}_{k\kappa} & \Omega^{\gamma}_{kK} & \Omega^{\gamma}_{kk} \end{vmatrix} < 0. \tag{46}$$

Given that

$$\begin{vmatrix} 0 & \Omega_{\kappa K} & \Omega_{\kappa k} \\ -s_K & \Omega^{\Gamma}_{KK} & \Omega^{\Gamma}_{Kk} \\ -S_k & \Omega^{\gamma}_{kK} & \Omega^{\gamma}_{kk} \end{vmatrix} = s_K\left(\Omega_{\kappa K}\Omega^{\gamma}_{kk} - \Omega_{\kappa k}\Omega^{\gamma}_{kK}\right) + S_k\left(\Omega_{\kappa k}\Omega^{\Gamma}_{KK} - \Omega_{\kappa K}\Omega^{\Gamma}_{Kk}\right), \tag{47}$$

we see that $\frac{d\kappa}{d\gamma} = 0$ if $s_K = S_k = 0$. With positive externalities, i.e. $s_K > 0$ and $S_k > 0$, the sign of (47) depends on the cross second derivatives $\Omega_{\kappa K}$,Ω^{γ}_{kK},$\Omega_{\kappa k}$,$\Omega_{\kappa K}$, Ω^{Γ}_{Kk}; if they are all positive, $\frac{d\kappa}{d\gamma} > 0$.

Similarly

$$\frac{dK}{d\gamma} = \frac{1}{\det(A)}\left[-s_K\left(\Omega_{\kappa\kappa}\Omega^{\gamma}_{kk} - \Omega_{\kappa k}\Omega^{\gamma}_{k\kappa}\right) + S_k\left(\Omega_{\kappa\kappa}\Omega^{\Gamma}_{Kk} - \Omega_{\kappa k}\Omega^{\Gamma}_{K\kappa}\right)\right], \tag{48}$$

$$\frac{dk}{d\gamma} = \frac{1}{\det(A)}\left[-S_k\left(\Omega_{\kappa\kappa}\Omega^{\Gamma}_{KK} - \Omega_{\kappa K}\Omega^{\Gamma}_{K\kappa}\right) + s_K\left(\Omega_{\kappa\kappa}\Omega^{\gamma}_{kK} - \Omega_{\kappa K}\Omega^{\gamma}_{k\kappa}\right)\right]. \tag{49}$$

Note that in both (48) and (49), the first element in brackets is negative by the second-order equilibrium conditions. Positive complementarity between capacities is sufficient to ensure that the remaining elements are also negative, so that $\frac{dK}{d\gamma} > 0$ and $\frac{dk}{d\gamma} > 0$. The result also holds when cross second derivatives are negative (i.e. when capacities are marginal substitutes) but small in absolute value.

Assuming that the conditions hold for all relevant γ, so that $\frac{d\kappa}{d\gamma}, \frac{dK}{d\gamma}, \frac{d\kappa}{d\gamma} > 0$, Proposition 2 follows.

Suppose the two countries are symmetric, i.e. $S(\kappa, K, k) \equiv s(\kappa, k, K)$, so that the equilibrium is symmetric also; in particular, $k = K$ at equilibrium. We can then write

$$\frac{d\kappa}{d\gamma} = \frac{1}{\det(A)} 2 s_K \Omega_{\kappa k}\left(\Omega^{\gamma}_{kk} - \Omega^{\gamma}_{kK}\right), \tag{50}$$

$$\frac{dK}{d\gamma} = \frac{-1}{\det(A)} s_K \Omega_{\kappa\kappa}\left(\Omega^{\gamma}_{kk} - \Omega^{\gamma}_{Kk}\right), \tag{51}$$

so that

$$\frac{dK}{d\gamma} - \frac{d\kappa}{d\gamma} = \frac{-1}{\det(A)} s_K\left(\Omega_{\kappa\kappa} + 2\Omega_{\kappa k}\right)\left(\Omega^{\gamma}_{kk} - \Omega^{\gamma}_{kK}\right).$$

If $\Omega_{\kappa k} < -\frac{1}{2}\Omega_{\kappa\kappa}$ and $\Omega^{\gamma}_{kK} > \Omega^{\gamma}_{kk}$, we have $\frac{dK}{d\gamma} > \frac{d\kappa}{d\gamma} > 0$. It then follows that $K^* - K^b = k^* - k^b > \kappa^* - \kappa^b$.

A.3 Regulation mechanism

In this section, we consider a possible mechanism to implement the optimal solution and the constraints that may impede its achievement.

A.3.1 The mechanism

Suppose that the two countries remain responsible for their domestic capacities, but that there exists a supranational agency in charge of designing an interconnector that will be financed by funds raised from the two countries.

Assuming linear contributions $TK + T_0$ and $tk + t_0$ from the two countries dedicated to cover the interconnector cost, the regulation game may be formulated as follows:

$$\max_{\kappa,T,t,T_0,t_0} \Phi\left(S\left(\kappa,K,k\right)-K\right)+\phi\left(s\left(\kappa,K,k\right)-k\right)-\kappa \tag{52}$$

subject to

$$TK+T_0+tk+t_0\geq\kappa,\ (\mu) \tag{53}$$

$$\begin{aligned} S(\kappa,K,k)-\left(\left(1+T\right)K+T_0\right) &\geq 0,\ (\mathit{\Theta}) & (54)\\ s(\kappa,K,k)-\left(\left(1+t\right)k+t_0\right) &\geq 0,\ (\theta) & (55)\end{aligned}$$

$$\begin{aligned} TK+T_0 &\leq F,\ (H) & (56)\\ tk+t_0 &\leq f,\ (\eta) & (57)\end{aligned}$$

In the objective function (52), the coefficients $\Phi\geq 1$ and $\phi\geq 1$ represent the influence of the two countries on the supranational agency. The dual variable of the financing constraint (53) is $\mu\geq 0$, while those of the individual rationality constraints (54) and (55) are $\mathit{\Theta}\geq 0$ and $\theta\geq 0$, respectively. In the individual rationality constraints, we have implicitly assumed that reservation values are nil, i.e. $\max_K S(0,K,k)-K=0$ and $\max_K s(0,K,k)-k=0$. Finally, we have assumed financing constraints in (56) and (57), with dual variables $H\geq 0$ and $\eta\geq 0$ respectively. These latter constraints may be seen as political restrictions imposed on national decision makers by their constituencies.

Given a mechanism $\{\kappa,T,T_0,t,t_0\}$ set by the supranational agency, and if transfers do not violate the constraints (54)-(57), the two countries determine their domestic investments $K(\kappa, k, T)$ and $k(\kappa, K, t)$, respectively, as solutions to

$$\begin{aligned} S_K(\kappa, K, k) &= 1 + T, & (58) \\ s_k(\kappa, K, k) &= 1 + t. & (59) \end{aligned}$$

Assume that the two countries play a non-cooperative Nash game to determine their domestic investment. Then $K(\kappa, k, T)$ and $k(\kappa, K, t)$ are to be viewed as best-response funtions, leading to the Nash equilibrium $\left\{K^N(\kappa, T, t), k^N(\kappa, T, t)\right\}$.

The Lagrange function of the agency's problem may be written

$$\begin{aligned} L &= (\Phi + \mathit{\Theta})(S - K) + (\phi + \theta)(s - k) \\ &\quad + (\mu - \mathit{\Theta} - H)(TK + T_0) + (\mu - \theta - \eta)(tk + t_0) - (1 + \mu)\kappa + HF + \eta f. \end{aligned}$$

where K, k, S and s are evaluated at $\left\{K^N, k^N\right\}$.

The first order conditions with respect to the fixed parts of the contributions, T_0 and t_0, are

$$\mu - \mathit{\Theta} - H = 0 = \mu - \theta - \eta. \tag{60}$$

It follows that the variable parts of the transfers, T and t, and the size of the interconnector, κ, are the solutions to

$$\max\nolimits_{T,t,\kappa} (\Phi + \mathit{\Theta})(S - K) + (\phi + \theta)(s - k) - (1 + \mu)\kappa.$$

The first-order condition with respect to T is

$$(\Phi + \mathit{\Theta})\left((S_K - 1)\frac{\partial K^N}{\partial T} + S_k\frac{\partial k^N}{\partial T}\right) + (\phi + \theta)\left((s_k - 1)\frac{\partial k^N}{\partial T} + s_K\frac{\partial K^N}{\partial T}\right) = 0.$$

Using (58) and (59), after rearranging we obtain

$$((\Phi + \mathit{\Theta})T + (\phi + \theta)s_K)\frac{\partial K^N}{\partial T} + ((\phi + \theta)t + (\Phi + \mathit{\Theta})S_k)\frac{\partial k^N}{\partial T} = 0. \tag{61}$$

Similarly, the first-order condition with respect to t may be written

$$((\Phi + \mathit{\Theta})T + (\phi + \theta)s_K)\frac{\partial K^N}{\partial t} + ((\phi + \theta)t + (\Phi + \mathit{\Theta})S_k)\frac{\partial k^N}{\partial t} = 0. \tag{62}$$

Finally, the first-order contition with respect to κ is

$$\left(\left(\Phi+\mathit{\Theta}\right)T+\left(\phi+\theta\right)s_{K}\right)\frac{\partial K^{N}}{\partial\kappa}+\left(\left(\phi+\theta\right)t+\left(\Phi+\mathit{\Theta}\right)S_{k}\right)\frac{\partial k^{N}}{\partial\kappa}$$
$$+\left(\Phi+\mathit{\Theta}\right)S_{\kappa}+\left(\phi+\theta\right)s_{\kappa}-\left(1+\mu\right)=0$$

For these three equations to be true for all values of $\frac{\partial K^N}{\partial T}$, $\frac{\partial k^N}{\partial T}$, $\frac{\partial K^N}{\partial t}$, $\frac{\partial k^N}{\partial t}$, $\frac{\partial K^N}{\partial \kappa}$ and $\frac{\partial k^N}{\partial \kappa}$ we must have

$$\begin{aligned} T &= -s_K\frac{\phi+\theta}{\Phi+\mathit{\Theta}}, \\ t &= -S_k\frac{\Phi+\mathit{\Theta}}{\phi+\theta}, \\ \left(\Phi+\mathit{\Theta}\right)S_{\kappa}+\left(\phi+\theta\right)s_{\kappa} &= 1+\mu. \end{aligned} \tag{63}$$

A.3.2 Balanced influence and non-restricted contributions

This case is represented by $\Phi=\phi=1$ and absence of constraints on contributions (56)-(57) or $H=\eta=0$. Then $\mathit{\Theta}=\mu=\theta$ by (60) and (63) becomes

$$T=-s_K,\ t=-S_k\ \text{ and } S_{\kappa}+s_{\kappa}=1. \tag{64}$$

We thus obtain the optimality condition for the interconnector, while plugging in the values for T and t in (64) in the Nash equilibrium (61) and (62) gives us the optimality conditions $S_K+s_K=1$ and $s_k+S_k=1$ for the two domestic investments.

In other words, in this environment, the supranational agency can implement the optimum by subsidising reinforcement of each national network up to the marginal positive externality it creates in the neighbouring country. The remaining problem is how to allocate the cost of the interconnector and the variable transfers $TK<0$ and $tk<0$ between the fixed contributions T_0 and t_0. Any combination of T_0 and t_0 that satisfy $TK+T_0+tk+t_0\geq\kappa$ without violating the constraints (54)-(55) is a solution. Note that one of the two fixed transfers may be negative; that is, either $T_0<0$ or $t_0<0$, as long the three constraints (53), (54) and (55) are satisfied.

A.3.3 Restricted contributions

We then move to a case in which $\Phi = \phi = 1$ but where the two constraints on contributions (56) and (57) must be satisfied. From (60) and (63) the solution is

$$\begin{aligned} T &= -\frac{1}{\Psi} s_K \\ t &= -\Psi S_k \\ \left(1 - \frac{H}{1+\mu}\right) S_\kappa + \left(1 - \frac{\eta}{1+\mu}\right) s_\kappa &= 1 \end{aligned} \tag{65}$$

where $\Psi = \frac{1+\mu-H}{1+\mu-\eta}$.

If at least one the constraints (56) and (57) is binding ($H > 0$ or $\eta > 0$), the interconnector will be undersized. The variable parts of the contributions (or subsidies) are distorted in a way that depends on the extent to which the individual financing constraints are binding (i.e. the relative size of H and η) as well as the relative importance of the externalities (s_K and S_k). For example, assume that $s_K >> S_k$. Then optimality would command $T << t$ for a strong incentive to invest in K and this would strongly increase $s(.)$. This efficiency argument could be used to justify $t_0 >> T_0$. However, it could result in $t_0 + tk > f$ that would violate (57). Then, $t_0 + tk = 0$ and $\eta > 0$ whereas $T_0 + TK < F$ and $H = 0$ resulting in $T = -s_K \left(1 - \frac{\eta}{1+\mu}\right) > -s_K$. With this weaker incentive, the investment in K is smaller than at the optimum because of the reluctance of the neighbouring country to participate in the financing of the interconnector. Note that with $\eta > 0$, by (60) we also have $\mu > 0$, which means that this type of "conflict" arises when the budget constraint (53) is binding.

A.3.4 Unequal influence

Suppose now that there is no constraint on the contributions such as (56) and (57), but that one country has more influence than the other on the supranational regulator, for example $\Phi > \phi = 1$. Then by (63) and (60) with $H = 0 = \eta$, we have

$$\begin{aligned} T &= -\frac{1}{\Xi} s_K \\ t &= -\Xi S_k \\ \Xi S_\kappa + s_\kappa &= 1 \end{aligned} \tag{66}$$

where $\Xi = \frac{\Phi+\mu}{1+\mu} > 1$.

Comparing with (64), investment is distorted towards a larger interconnector. Regarding the variable parts of the contribution, the more influential country receives less than at optimum ($T = -\frac{1}{\Xi} s_K > -s_K$) while the less influential country receives more ($t = -\Xi S_k < -S_k$). This is a kind of cross-subsidisation to promote domestic investment in the less influential country. By (60), $\mathit{\Theta} = \mu = \theta \geq 0$ so that the fixed parts of the contributions, T_0 and t_0, can take any value that does not violate the constraints (53)-(55).