

Decentralised Cross-Border Interconnection

Claude Crampes and
Nils-Henrik M. von der Fehr



Working Paper 11/2018



CREE – Oslo Centre for Research on Environmentally Friendly Energy
acknowledges financial support from
The Research Council of Norway, University of Oslo and user partners.

ISBN: 978-82-7988-265-7

ISSN: 1892-9680

<http://www.cree.uio.no>

Decentralised Cross-Border Interconnection

Claude Crampes* and Nils-Henrik M. von der Fehr†

12th November 2018

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.

Acknowledgement: We are grateful for helpful comments from Fridrik Baldursson and participants at CRESSE 2016.

JEL codes: H77, K23, L51, L94

Keywords: electrical grid, externality, regulaties, regional cooperation

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 national 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 national transmissions systems that would be warranted to achieve the full benefits of interconnection. As a result, such projects tend to be suboptimal, or they are not undertaken at all. Two recent examples from France and Spain may illustrate the difficulties.

*Toulouse School of Economics, claude.crampes@tse-fr.eu

†University of Oslo, nhfehr@econ.uio.no

In 2008, the electricity transmission and system operators of France and Spain, respectively 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.¹ The line, inaugurated in February 2015, is the first interconnection between France and Spain brought into service in almost 30 years. The direct-current line is entirely underground, with a length of 64.5 kilometres, and represented an investment of 700 million euros. By doubling the exchange capacity from 1,400 MW to 2,800 MW, it is expected to increase the security, stability and quality of power supply in both countries; in particular, the new infrastructure is expected to guarantee the electrical power supply for high-speed trains on the Spanish side, as well as allowing for the integration of a greater volume of wind energy from the Iberian system.

In a report published by the French regulator in November 2015,² it appeared that the commercial capacity effectively made available to the market in 2016 would 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 this interconnection are reduced as market participants have less exchange capacity than planned to optimise at a regional level.

The Inelfe electrical interconnector has some similarities with the Midi-Catalogne

¹http://www.inelfe.eu/IMG/pdf/Spain_France_electrical_interconnection_ENG-compressed.pdf

²Deliberation 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>.

(Midcat) project to connect France and Spain with a gas pipe.³ Brussels and Madrid are strongly in favour of the ten-year old project to import excess natural gas arriving in Spain by pipes from Algeria and from methane terminals in several different locations,⁴ a main motivation being to lower the dependency on natural gas coming from the east of Europe.⁵ For the project to be successful, France will have to invest heavily to reinforce its domestic network: a cost of 2.3 billion euros – out of 3.1 billion euros for the whole project – would be passed on to French consumers. Paris is not very enthusiastic about a project that would to a large extent be financed by French consumers in order to increase security of supply in all of Western Europe. At the beginning of April 2016, the European Commission funded two engineering studies to develop Midcat, and contracts have been signed with Enagas and TIGF, the Spanish and French gas transmission system operators. Funding will come from the Connecting Europe Facility, the Commission’s programme to finance energy infrastructure, and will cover up to 50 percent of the real costs. However, traders are skeptical⁶ and it remains to be seen if the project will eventually go ahead.

The difficulties arising from decentralised decision-making in an integrated network has 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 progress 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) (see www.entsoe.eu) and European Network for Transmission Operators for Gas (ENTSO-G)(see www.entsog.eu); 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 Commissions selection of so-called Projects of Common Interest. In the 2016 Winter Package (European Commission, 2016)⁷, the European Commission foresees the establishment of re-

³<http://www.platts.com/latest-news/natural-gas/london/analysis-traders-skeptical-on-french-spanish-26240144>

⁴Six are operational, two others are being built; www.europarl.europa.eu/RegData/etudes/BRIE/2015/571314/EPF

⁵<http://www.euractiv.com/sections/energy/spanish-midcat-pipeline-replace-10-russian-gas-imports-301205>

⁶<http://www.platts.com/latest-news/natural-gas/london/analysis-traders-skeptical-on-french-spanish-26240144>

⁷<https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition>

gional entities which would take over functions and responsibilities from national transmission system operators.⁸ Nevertheless, even though much has happened to coordinate decisions on energy infrastructure in Europe, it is still the case that, within their jurisdictions, national regulators and system operators have discretion.

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.⁹ Interconnectors generate revenue based on price arbitrage between nodes. When there is a difference in nodal prices, there will be demand for transmission capacity and a revenue stream may be generated. 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, 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.¹⁰ The prospects and problems of transmission investment also vary depending on whether it is purely merchant or under tight regulation.¹¹ 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. In de Jong et al. (2007), one finds 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)

⁸Regionalisation of the electricity sector was recently analysed in Crampes, von der Fehr and Steel (2017); see also Bohne (2011) and Kolk (2014).

⁹See for example Joskow and Tirole (2000).

¹⁰See 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.

¹¹'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).

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.¹² Both national and European regulators scrutinize transmission system operators' activities. Each organization has powers that affect the transmission system operators' decisions on interconnection. The theory of multiple principals provides a useful tool-box for the analysis of interacting incentives designed by different regulators. The subsidiarity principle, according to which, loosely speaking, decentralisation is desirable unless it entails too high coordination costs and too little internalisation, is also helpful in assessing the proper level of decentralisation. 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,¹³ discussing how the regulatory structure should evolve and how the relationships between an international transmission system operator and its regulator(s) could be altered.¹⁴

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. 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.

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

¹²It is based on an analytical framework designed by Caillaud, Jullien, and Picard (1996).

¹³This part of the analysis is based on an article by Laffont and Pouyet (2003), who discuss the role of shareholders and lobbyists in the regulation process.

¹⁴Castaneda 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.

in the installation of an interconnector linking their respective networks. After a presentation of the assumptions of the model, we determine first-best 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, $S_\kappa, s_\kappa, S_K, s_k > 0$, 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.¹⁵ 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 $i, j = \kappa, K, k$. 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 complementarities below, i.e. $S_{kK}, s_{kK} > 0$, we also consider the case

¹⁵A 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 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 $S_k = 0$.

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:

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

This Cobb-Douglas-like specification has properties lying between complete substitutability, 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 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

$$W(\kappa, K, k) = S(\kappa, K, k) - K - \theta\kappa, \quad (2)$$

$$w(\kappa, K, k) = s(\kappa, K, k) - k - (1 - \theta)\kappa, \quad (3)$$

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

Maximisation of the sum of net surpluses,

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

leads to the following first-order conditions:

$$S_\kappa + s_\kappa = S_K + s_K = S_k + s_k = 1. \quad (5)$$

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 $s_K > 0$, domestic capacities are public goods also. 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 example, the sum of net surpluses becomes

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

From the first-best conditions (5), we find that the optimal solutions is

$$\kappa^* = K^* = k^* = 1, \quad (7)$$

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:

$$\max_{\kappa, \theta} W^\alpha w^{1-\alpha}, \quad (8)$$

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 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 , we get

$$\frac{w}{W} = \frac{\alpha}{1 - \alpha}. \quad (9)$$

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 $\alpha \rightarrow 1$ (respectively 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

$$\alpha W (S_\kappa - \theta) + (1 - \alpha) w (s_\kappa - (1 - \theta)) = 0. \quad (10)$$

Using (9), (10) reduces to

$$S_\kappa + s_\kappa = 1. \quad (11)$$

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 bargaining 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. The two countries solve, respectively,

$$\max_K W, \quad (12)$$

$$\max_k w, \quad (13)$$

leading to the first-order conditions

$$S_K = s_k = 1. \quad (14)$$

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

Comparing (11) and (14) with (5), it follows that, absent any domestic externalities, 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 $s_K \equiv 0$, $\{\kappa^b, K^b, k^b\} = \{\kappa^*, K^*, k^*\}$.*

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 first-best level and the interconnector will also be undersized if it is a marginal complement to internal lines.

More specifically, we have:

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

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

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

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

Proof. The full proof is in the Appendix, and here we just provide a sketch. Consider the modified surplus functions Ω^F and Ω^f for the two countries respectively, where γ is a parameter measuring the degree of "altruism" in each country. If $\gamma = 0$, we 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 first best. 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) $\Omega_{\kappa\kappa}\Omega_{kk}^\gamma - \Omega_{\kappa k}\Omega_{k\kappa}^\gamma > 0$ and $\Omega_{\kappa\kappa}\Omega_{KK}^\Gamma - \Omega_{\kappa K}\Omega_{K\kappa}^\Gamma > 0$, $K^b < K^*$ and $k^b < k^*$ if $\Omega_{\kappa\kappa}\Omega_{Kk}^\Gamma - \Omega_{\kappa k}\Omega_{K\kappa}^\Gamma$ and $\Omega_{\kappa\kappa}\Omega_{kK}^\gamma - \Omega_{\kappa K}\Omega_{k\kappa}^\gamma$ 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 first-best 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 $\gamma \in [0, 1]$, $(\Omega_{\kappa\kappa} + 2\Omega_{\kappa k})(\Omega_{kk}^\gamma - \Omega_{kK}^\gamma) > 0$. 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. $\Omega_{kK}^\gamma > \Omega_{kk}^\gamma$.

Example. The above results hold in our example. The equilibrium conditions with partial cooperation (11) and (14) imply

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

with the value of the sum of net surpluses now being $\Omega^b = \frac{1}{2}$. Comparing the equilibrium outcome with the first best, 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 first-best values.

3 Policy Analysis

To restore first best, 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.¹⁶ 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

$$S_\kappa + s_\kappa = 1 - \sigma, \quad (19)$$

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

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

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

¹⁶The 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.

follows that

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

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

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

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:

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

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

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

$$\frac{dQ}{d\sigma}_{\sigma=0} = S_k \frac{dk}{d\sigma} + s_K \frac{dK}{d\sigma} > 0. \quad (25)$$

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 first best.*

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 first-best levels. On the other hand, the interconnector capacity increases faster than domestic capacities, thereby increasing the relative gap between equilibrium and first-best levels.

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

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

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

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

With $\sigma = \frac{1}{2}$ interconnection capacity is at the first-best 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 first-best 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

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

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 first-best 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,

$$\max_K S(\kappa, K, k) - (1 + T)K - T_0 \quad (29)$$

$$\max_k s(\kappa, K, k) - (1 + t)k - t_0, \quad (30)$$

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

The first-order conditions for these problems are

$$S_K(\kappa, K, k) = 1 + T, \quad (31)$$

$$s_k(\kappa, K, k) = 1 + t. \quad (32)$$

Clearly, by setting

$$T = -s_K(\kappa^*, K^*, k^*), \quad (33)$$

$$t = -S_k(\kappa^*, K^*, k^*), \quad (34)$$

and assuming that interconnector capacity is determined as above by condition (11), we obtain the first-best conditions (5) for all capacities. In the Appendix, we suggest a mechanism to implement this solution and provide a formal proof of the result.

Apart from the absence of a super-national institution with the power to introduce such regulation, implementation would meet with at least two difficulties. The first is the standard regulatory problem of asymmetric information; as is evident from (33) and (34), in order to implement the first-best the regulator would need to know not only optimal capacities, but also the externalities caused by these.

The second difficulty has to do with 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 are required in France in order for Spain to reap benefits, is an example of how such difficulties may preclude cross-border agreement.

4 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 strongly 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 necessarily 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 Midcat project being one example). Analysis of such cases would require a different framework than ours.

References

- [1] Bohne, E. (2011), Conflicts between national regulatory cultures and EU energy regulations, *Utilities Policy* 19 (4), 255-69.
- [2] Brunekreeft, Gert, Neuhoff, Karsten and David Newbery (2005), Electricity transmission: an overview of the current debate, *Utilities Policy* 13 (2), 73-93.
- [3] Caillaud, B., B. Jullien, and P. Picard (1996), National vs. European incentive policies: bargaining, information and coordination, *European Economic Review* 40, 91–111.
- [4] Castaneda, A., M.A. Jamison, and M. Phillips (2015), Adaptive Regulatory Systems, PURC, University of Florida, December (<https://www.aeaweb.org/aea/2016conference/program/retrieve.php?pdfid=602>).
- [5] Crampes, Claude, Nils-Henrik M. von der Fehr and Graeme Steel (2017), Review of the Electricity Market Design in the Context of the Energy Union: The Role of Regions, Project Report, Centre on Regulation in Europe, 23 February (http://www.cerre.eu/sites/cerre/files/170223_CERRE_ElectricityRegions_Final_0.pdf).
- [6] Crampes, Claude and Lucile Rives (2011), Regulating electricity transmission in the European Union - how many agencies?, Chapter 4 in A. Estache (ed), *Emerging Issues in Competition, Collusion, and Regulation of Network Industries*, CEPR, 57-77 (http://www.tse-fr.eu/sites/default/files/TSE/documents/doc/by/crampes/rives_january_2011.pdf).
- [7] ENTSO-E (2014), Fostering Electricity Transmission Investments to Achieve Europe’s Energy Goals: Towards a Future-Looking Regulation, Policy Paper, European Network of Transmission System Operators for Electricity, 26 November (https://www.entsoe.eu/Documents/Publications/Position%20papers%20and%20reports/14112_E_Policy_Paper_Fostering_Electricity_Transmission_Investments.pdf).

- [8] European Commission (2015), Commission Regulation Establishing a Guideline on Capacity Allocation and Congestion Management, Regulation 2015/1222, (<http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R1222&from=EN>).
- [9] European Commission (2016), Winter Package (<https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition>).
- [10] European Council (2009a), Regulation (EC) No 713/2009 of the European Parliament and of the Council of 13 July 2009 establishing an Agency for the Cooperation of Energy Regulators (<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0001:0014:EN:pdf>)
- [11] European Council (2009b), Regulation (EC) No 714/2009 of the European parliament and of the Council of 13 July 2009 on Conditions for Access to the Network for Cross-Border Exchanges in Electricity and Repealing Regulation (EC) No 1228/2003 (<http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0714&from=EN>).
- [12] de Jong H M., J C van der Lippe and H P A. Knops (2007), Investment in Cross Border Transmission Capacity: Economics or Politics? A European Case Study, Delft University of Technology, (http://www.nextgenerationinfrastructures.eu/catalog/file/449424/USAEE_06_Knops.pdf).
- [13] Joskow Paul L and Jean Tirole (2000), Transmission rights and market power on electric power networks, *RAND Journal of Economics* 31 (3), 450–87.
- [14] Kolk, A, J Lindeque and D van den Buuse (2014), Regionalization strategies of EU electric utilities, *British Journal of Management* 25 (S1), S77–S99.
- [15] Laffont, Jean Jacques and J Pouyet (2003), The subsidiarity bias in regulation, *Journal of Public Economics* 88, 255–83.
- [16] Ofgem (2013), Cap and Floor Regime for Regulated Electricity Interconnector Investment for application to project NEMO - Consultation Document, Office of Gas and Electricity Markets, March 7 (https://www.ofgem.gov.uk/sites/default/files/docs/2013/03/cap-and-floor-regime-for-regulated-electricity-interconnector-investment--for-application-to-project-nemo_0.pdf).

A Appendix

A.1 Concavity conditions

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

$$\begin{bmatrix} S_{\kappa\kappa} & S_{\kappa K} & S_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ S_{k\kappa} & S_{kK} & S_{kk} \end{bmatrix}, \begin{bmatrix} s_{\kappa\kappa} & s_{\kappa k} & s_{\kappa K} \\ s_{k\kappa} & s_{kk} & s_{kK} \\ s_{K\kappa} & s_{Kk} & s_{KK} \end{bmatrix} \quad (35)$$

are negative definite. In terms of determinants, we have

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

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

$$\Omega_\kappa = \Omega_K^\Gamma = \Omega_k^\gamma = 1, \quad (36)$$

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

We consider the solution to (36) as a function of γ :

$$\begin{bmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega_{K\kappa}^\Gamma & \Omega_{KK}^\Gamma & \Omega_{Kk}^\Gamma \\ \Omega_{k\kappa}^\gamma & \Omega_{kK}^\gamma & \Omega_{kk}^\gamma \end{bmatrix} \begin{bmatrix} d\kappa \\ dK \\ dk \end{bmatrix} = \begin{bmatrix} 0 \\ -s_K d\gamma \\ -s_k d\gamma \end{bmatrix}. \quad (37)$$

The matrix on the left-hand side of (37) may be written

$$\begin{bmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega_{K\kappa}^\Gamma & \Omega_{KK}^\Gamma & \Omega_{Kk}^\Gamma \\ \Omega_{k\kappa}^\gamma & \Omega_{kK}^\gamma & \Omega_{kk}^\gamma \end{bmatrix} = \begin{bmatrix} S_{\kappa\kappa} & S_{\kappa K} & S_{\kappa k} \\ S_{K\kappa} & S_{KK} & S_{Kk} \\ \gamma S_{k\kappa} & \gamma S_{kK} & \gamma S_{kk} \end{bmatrix} + \begin{bmatrix} s_{\kappa\kappa} & s_{\kappa k} & s_{\kappa K} \\ \gamma s_{k\kappa} & \gamma s_{kk} & \gamma s_{kK} \\ s_{K\kappa} & s_{Kk} & s_{KK} \end{bmatrix}. \quad (38)$$

Given that the two matrices in (35) are negative definite, it is easily seen that so are the two matrices on the right-hand side of (38). It follows that the matrix on the left-hand side of (38) – 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 (37), we obtain

$$\frac{d\kappa}{d\gamma} = \frac{1}{\det(A)} \begin{vmatrix} 0 & \Omega_{\kappa K} & \Omega_{\kappa k} \\ -s_K & \Omega_{KK}^\Gamma & \Omega_{Kk}^\Gamma \\ -s_k & \Omega_{kK}^\gamma & \Omega_{kk}^\gamma \end{vmatrix}, \quad (39)$$

where

$$\det(A) = \begin{vmatrix} \Omega_{\kappa\kappa} & \Omega_{\kappa K} & \Omega_{\kappa k} \\ \Omega_{K\kappa}^\Gamma & \Omega_{KK}^\Gamma & \Omega_{Kk}^\Gamma \\ \Omega_{k\kappa}^\gamma & \Omega_{kK}^\gamma & \Omega_{kk}^\gamma \end{vmatrix} < 0. \quad (40)$$

Given that

$$\begin{vmatrix} 0 & \Omega_{\kappa K} & \Omega_{\kappa k} \\ -s_K & \Omega_{KK}^\Gamma & \Omega_{Kk}^\Gamma \\ -s_k & \Omega_{kK}^\gamma & \Omega_{kk}^\gamma \end{vmatrix} = s_K (\Omega_{\kappa K} \Omega_{kk}^\gamma - \Omega_{\kappa k} \Omega_{kK}^\gamma) + s_k (\Omega_{\kappa k} \Omega_{KK}^\Gamma - \Omega_{\kappa K} \Omega_{Kk}^\Gamma), \quad (41)$$

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 (41) depends on the cross second derivatives $\Omega_{\kappa K}, \Omega_{kK}^\gamma, \Omega_{\kappa k}, \Omega_{\kappa K}, \Omega_{Kk}^\Gamma$; if they are all positive, $\frac{d\kappa}{d\gamma} > 0$.

Similarly

$$\frac{dK}{d\gamma} = \frac{1}{\det(A)} [-s_K (\Omega_{\kappa\kappa} \Omega_{kk}^\gamma - \Omega_{\kappa k} \Omega_{k\kappa}^\gamma) + s_k (\Omega_{\kappa\kappa} \Omega_{Kk}^\Gamma - \Omega_{\kappa K} \Omega_{K\kappa}^\Gamma)], \quad (42)$$

$$\frac{dk}{d\gamma} = \frac{1}{\det(A)} [-s_k (\Omega_{\kappa\kappa} \Omega_{KK}^\Gamma - \Omega_{\kappa K} \Omega_{K\kappa}^\Gamma) + s_K (\Omega_{\kappa\kappa} \Omega_{kK}^\gamma - \Omega_{\kappa K} \Omega_{k\kappa}^\gamma)]. \quad (43)$$

Note that in both (42) and (43), 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

$$\frac{d\kappa}{d\gamma} = \frac{1}{\det(A)} 2s_K \Omega_{\kappa k} (\Omega_{kk}^\gamma - \Omega_{kK}^\gamma), \quad (44)$$

$$\frac{dK}{d\gamma} = \frac{-1}{\det(A)} s_K \Omega_{\kappa k} (\Omega_{kk}^\gamma - \Omega_{kK}^\gamma), \quad (45)$$

so that

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

If $\Omega_{\kappa k} < -\frac{1}{2}\Omega_{\kappa\kappa}$ and $\Omega_{kK}^\gamma > \Omega_{kk}^\gamma$, 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 first-best solution. Suppose that the two countries remain responsible for their domestic capacities, but that there exists an agency in charge of designing an interconnector that will be financed by funds raised from the two countries. Assuming a linear transfer, the regulation game may be formulated as follows:

$$\max_{\kappa, T, T_0, t, t_0} TK + T_0 + tk + t_0 - \kappa, \quad (46)$$

subject to

$$\max_K S(\kappa, K, k) - ((1 + T)K + T_0) \geq 0, \quad (47)$$

$$\max_k s(\kappa, K, k) - ((1 + t)k + t_0) \geq 0, \quad (48)$$

where we have assumed that the reservation value is zero for both countries.

Given a mechanism $\{\kappa, T, T_0, t, t_0\}$ set by the agency, and if the transfers do not violate the non-negativity constraints (47) and (48), the two countries determine their domestic investments $K(\kappa, k, T)$ and $k(\kappa, K, t)$, respectively, as solutions to

$$S_K(\kappa, K, k) = 1 + T, \quad (49)$$

$$s_k(\kappa, K, k) = 1 + t. \quad (50)$$

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 functions, leading to the Nash equilibrium $\{K^N(\kappa, T, t), k^N(\kappa, T, t)\}$. The resulting national net surpluses are

$$S(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)) - (1 + T)K^N(\kappa, T, t) - T_0, \quad (51)$$

$$s(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)) - (1 + t)k^N(\kappa, T, t) - t_0. \quad (52)$$

As the objective function of the agency is increasing in T_0 and t_0 , it chooses the fixed parts of the transfer that strictly satisfy the individual rationality constraints (47) and (48):

$$(1 + T)K^N(\kappa, T, t) + T_0 = S(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)), \quad (53)$$

$$(1 + t)k^N(\kappa, T, t) + t_0 = s(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)). \quad (54)$$

Then it remains to solve

$$\begin{aligned} \max_{\kappa, T, t} S(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)) + s(\kappa, K^N(\kappa, T, t), k^N(\kappa, T, t)) \\ - K^N(\kappa, T, t) - k^N(\kappa, T, t) - \kappa. \end{aligned} \quad (55)$$

The first-order conditions are

$$\kappa : S_\kappa + s_\kappa + (S_K + s_K - 1)K_\kappa^N + (S_k + s_k - 1)k_\kappa^N = 1, \quad (56)$$

$$T : (S_K + s_K - 1)K_T^N + (S_k + s_k - 1)k_T^N = 0, \quad (57)$$

$$t : (S_K + s_K - 1)K_t^N + (S_k + s_k - 1)k_t^N = 0, \quad (58)$$

Using (49) and (50) we obtain

$$\kappa : S_\kappa + s_\kappa + (T + s_K)K_\kappa^N + (t + s_k)k_\kappa^N = 1, \quad (59)$$

$$T : (T + s_K)K_T^N + (t + s_k)k_T^N = 0, \quad (60)$$

$$t : (T + s_K)K_t^N + (t + s_k)k_t^N = 0. \quad (61)$$

Clearly, by fixing

$$T = -s_K, t = -S_k, \tag{62}$$

we satisfy the two last conditions. The Nash equilibrium (49) and (50) then gives us first-best conditions $S_K + s_K = 1$ and $s_k + S_k = 1$ for the two domestic investments. Plugging the two transfer values into (62), we also obtain first-best condition for the interconnector,

$$S_\kappa + s_\kappa = 1,$$

as expected.