Optimal transmission regulation of an integrated energy market

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Abstract

The capacity of the transmission network determines the extent of integration of a multi-national energy market. Cross-border externalities render coordination of network capacity valuable. Is it then optimal to collect regulatory powers in the hands of a single regulator? Should a common system operator manage the entire network? I show that optimal network governance depends on (*i*) whether the centralized regulatory agency is able to balance the interests of the different countries; (*ii*) asymmetries across countries in the gains from market integration; (*iii*) network characteristics (substitutability versus complementarity); and (*iv*) the social cost of operator rent.
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1 Introduction

The European Commission (2007) views the completion of an integrated European energy market as essential for ensuring competitiveness, sustainability and security of energy supply in Europe. Market integration depends crucially on the transmission network connecting the member states being capable of reliably transporting energy from power plants in one country to consumers in another. Increasing shares of solar and wind energy place additional requirements on the grid as production and energy flows become more volatile. The transmission network is considered a natural monopoly in many countries. In a monopoly setting, establishing an efficient transmission network boils down to implementing a well designed regulatory policy.

Most liberalized electricity markets have been restructured one country at a time. Owing to the national scope of liberalization, transmission regulation has also been national in scope. National regulatory agencies govern national system operators who own and manage the national transmission networks. The question is whether transmission governance along national borders is still optimal in a multi-national energy market. In an integrated energy market, improvements in grid capacity at home have implications even abroad because the removal of each transmission bottleneck affects energy flows and prices across the entire market. With too narrow a focus on domestic effects, national regulatory agencies run the risk of ignoring externalities abroad when devising regulatory policy for the national system operator.

Two examples from the Nordic electricity market illustrate the influence of narrow national interests over transmission management. The Nordic electricity market constituted the world's first multi-national liberalized electricity market and now spans Denmark, Finland, Norway and Sweden.[1] In the spring of 2008, a number of transmission lines connecting southern Norway and southern Sweden broke down, severely limiting export capacity to Sweden. According to the Norwegian regulator, the line failures were largely due to insufficient maintenance by the Norwegian system operator, Statnett. Admitting that the repairs were taking an unusually long time, Statnett emphasized that the security of supply for Norwegian consumers was never jeopardized. Meanwhile, the consumers in southern Norway had been enjoying comparatively low electricity prices. The effects on consumers and producers in Sweden (or elsewhere) seem to have been absent from the Norwegian discussion.

In 2010, the European competition authority warned the Swedish system operator Svenska Kraftnät that the practice of alleviating domestic congestion problems by limiting exports to Denmark could be illegal. By cutting the outflow of electricity, Svenska Kraftnät was able to offset excess demand in southern Sweden, thereby achieving its objective of a uniform electricity price across Sweden. Danish interests, concerned with higher electricity prices in Denmark, filed a complaint with the EU accusing Svenska Kraftnät of abusing its monopoly position as the sole provider of Swedish transmission capacity. Svenska Kraftnät has subsequently decided to solve Swedish congestion problems through means other than reducing export capacity.[2]

[1] In addition, the Nordic market has interconnections with Estonia, Germany, Poland, Russia and The Netherlands.

[2] The measures include dividing Sweden into multiple price areas and transmission investments to remove domestic bottlenecks.

With the cross-border externalities in mind, would it not be better to establish a common regulatory agency responsible for the entire transmission network? And should the national system operators be merged into a common system operator? In this paper I formally analyze these *horizontal* aspects of network governance. The discussion has, so far, centered around the costs and benefits of *vertical* separation of transmission operation from production; see e.g. Cremer et al. (2006) for an analysis and Pollitt (2008) for an account of the arguments. For the fear of integrated utilities discriminating against competitors and investing inadequately in their networks, the EU recommends full ownership unbundling of transmission and production assets (EU, 2009b). However important vertical structure may be, overall network performance depends crucially on the incentives induced by the regulatory policies adopted by the different member states. The newly established Agency for the Cooperation of Energy Regulators (ACER) reflects this concern. ACER is furnished with the task of coordinating transmission regulation across the EU member states and deciding on the terms and conditions for access to cross-border infrastructure in case of national disagreement. On the system level, The European Network of Transmission System Operators for Electricity (ENTSO-E) is a collaboration of the system operators in the EU with the objective of coordinating and promoting system operator interests.

I consider a two-country energy market with interconnected networks. Network reliability is a measure of market integration and increases with maintenance spending in both networks. Gains from energy trade render network reliability valuable, but maintenance and transfer payments are costly. The purpose of regulation is to provide the system operators with the appropriate incentives for network maintenance while minimizing maintenance cost and transfer payments. First-best optimal spending occurs at the point at which the marginal benefit of network reliability equals the marginal social maintenance cost.[3]

	National regulatory agencies	Common regulatory agency
National system operators	*Separation*	*Common regulation*
Common system operator	*Common agency*	*Integration*

Table 1: A taxonomy of network governance structures

Network governance is a question of both how many regulators there should be and the optimal number of system operators (transmission owners). Therefore, a taxonomy of network structures needs to be compared with one another. The Nordic electricity market exemplifies the governance structure labelled *Separation* in Table 1. Separation constitutes the most decentralized network structure: Every country has its own national system operator (NSO) regulated

[3]Obviously, the regions do not necessarily have to be countries. The model could equally well be applied to study market integration between regional electricity markets in the US or elsewhere. Also, it is not necessary that electricity is traded on a common power exchange. In fact, the electricity markets do not even have to be liberalized. The crucial assumptions in the model are that capacity expansions are costly, capacity changes have effects on welfare in both regions, and there could be strategic interaction between regions in the decision to expand capacity. It follows that the qualitative insights gained in this paper regarding network reliability versus maintenance cost carry over to the long-run problem of network capacity versus investment cost.

by a national regulatory agency (NRA). An advocated contender is full centralization, here labeled *Integration*, where the responsibility for managing the entire transmission grid is merged in a common system operator (CSO), supervised by a common regulatory agency (CRA). *Common regulation* constitutes a compromise between Separation and Integration and features a set of NSOs jointly regulated by a CRA. An example of Common regulation is Great Britain, where Ofgem regulates the three transmission owners National Grid Electricity Transmission, Scottish Power Transmission Limited and Scottish Hydro-Electric Transmission Limited. To complete the picture, *Common agency* describes a situation where multiple national regulatory agencies independently regulate a single CSO. In practice, proponents of a single system operator typically envision a complementary coordination of regulatory policies. For example, an investigation of the desirability of a single Nordic system operator concluded that national governments should simultaneously be forced to relinquish some (regulatory) autonomy, otherwise interference from the national governments would create inefficiencies in system operation (EMG, 2008). I therefore skip a detailed analysis of Common agency at this stage, although one might want to consider it for the sake of completeness.

To compare welfare under the different structures, I assume that the common regulator selects the (for him) optimal regulatory policy. Under Separation, on the other hand, the two national regulatory agencies (NRAs) play a non-cooperative game against each other: Each NRA chooses its regulatory policy to maximize national welfare given the choice of policy by the other NRA.

A benevolent common regulator who can commit to complete long-term contracts can always replicate any set of contracts implemented by the national regulatory agencies and can potentially do better. Centralized regulation is always optimal in this case. Therefore, decentralized regulation can be optimal only if (*i*) the regulator is non-benevolent; or (*ii*) the regulator has commitment problems; or (*iii*) there are problems of contractual incompleteness at the centralized level. This paper analyses regulation from a political economy standpoint.[4] The countries differ in their valuation of market integration because of cross-country differences in the gains from trade. The common regulator maximizes a weighted average of national welfare in the two countries, where the weights are meant to capture the political influence of the respective countries over the design of the common regulatory policy.

The trade-off between centralized and decentralized regulation is between internalizing cross-border externalities of market integration and tailoring regulatory policies to each individual country to reflect differences in the valuation of market integration. National regulatory agencies (NRAs) provide insufficient incentives for network maintenance because they only consider the domestic and not the foreign gains from market integration. In addition, total maintenance spending is suboptimally distributed across the network because of a lack of coordination between the NRAs. Establishing a common regulatory agency (CRA) takes care of the coordina-

[4] Olsen and Torsvik (1993) analyze the case of non-commitment. They show that decentralized regulation can mitigate dynamic inefficiencies stemming from post-contractual exploitation by the centralized regulator. The system operator performs a multitude of tasks, such as short-term balancing of energy supply (Rious et al., 2008), all of which are not fully contractible. Incomplete contracting and optimal delegation in integrated energy markets are interesting topics for future research.

tion problem. However, total maintenance spending can be too high or too low under centralized regulation depending on the weight of the different countries in the objective function of the common regulator. If, for example, a country with very little to gain from market integration controls the CRA, maintenance incentives are vastly insufficient because the CRA grossly understates the value of market integration. In this case, regulatory decentralization is preferable to centralization. The key to establishing a well-functioning common regulatory agency thus lies in ensuring a balanced political influence across countries. With sufficiently equal distribution of political power, no country can exert enough influence over the regulatory policy to tilt it in one's own favour.

The externality/bias trade-off is classical in studies of political integration and dates back at least to Oates (1972). Ellingsen (1998) notes how asymmetric gains from integration favour decentralization. The importance of political balance for the desirability of centralization has gone relatively unnoticed, as far as I understand (although the result is straightforward), possibly because most models assume majority voting. Laffont and Pouyet (2003) are an exception. They analyze the costs and benefits of decentralized policies in a multi-national procurement model. Unlike in the present paper where political conflict is between countries (inter-jurisdictional conflict), Laffont and Pouyet (2003) assume that political conflict is between shareholders and non-shareholders (intra-jurisdictional conflict). The centralized buyer places less weight on consumer surplus than firm rent if shareholders are in majority, but cares nothing about firm rent if shareholders are in minority. Opposite to this paper, centralized procurement is found to welfare dominate decentralized procurement if and only if influence is asymmetrically distributed between shareholders and non-shareholders. This result can be traced to a peculiar specification of the objective function of the centralized buyer in their model: Under shareholder majority consumer surplus weighs more the larger is shareholder majority. Consumer surplus and firm rent have near equal weights in the limit when almost everybody is a shareholder, in which case the centralized buyer acts almost as the benevolent social planner.

Consider next the optimal number of system operators. An informational asymmetry is the source of an agency problem between the regulator(s) and the system operator(s). The regulator has insufficient information to assess whether network performance is inferior for exogenous reasons (low productivity) or endogenous reasons (insufficient maintenance). By understating the productivity of the network, a system operator can secure itself excessive transfer payments relative to the cost of maintaining the network. All else equal, the regulator would prefer to minimize this *informational rent* because transfer payments are costly to society. *Network complementarity* means a higher marginal value of maintenance spending in one part of the network, the higher is productivity in the other part of the network. An NSO understating productivity then imposes a *negative informational rent externality* on the foreign NSO because of reduced maintenance spending and lower transfer payments in the foreign network. By merging system operation in a single CSO, the regulator forces the network owners to internalize this negative rent externality - thereby reducing overall informational rent.

In the opposite case of network substitutability, a CSO may have an incentive to underreport productivity in one part of the network in order to increase the marginal value of maintenance spending and informational rent in the other part of the network. It is optimal to split system operation between two NSOs to prevent the CSO from internalizing this *positive informational rent externality*. However, network substitutability is only a necessary, but not sufficient condition for a positive informational rent externality to arise under a single CSO. A cost complementarity works in the opposite direction. The agency problem is exacerbated in the presence of a CSO because all information about the network is centralized in the hands of a single agent. The superior ability of the CSO to jointly understate productivity in all parts of the network renders it particularly costly to maintain high reliability in a network of uniformly low productivity, because of the additional informational rent. Thus, a CSO understating productivity (i.e. exaggerating maintenance cost) in one part of the network simultaneously exaggerates the (virtual) marginal maintenance cost in the other part of the network. Nevertheless, cost complementarity is weak relative to network substitutability if the social cost of transfer payments is low. In this case, a common regulator would optimally split system operation between multiple national system operators.

Dana (1993) and Gilbert and Riordan (1995) are the first to observe that a negative informational rent externality stemming from complementarities in production favours monopoly production. Mookherjee and Tsumagari (2004) generalize these findings by showing that multiple agents are optimal under a positive informational rent externality. Severinov (2008) explores the technological foundations of rent externalities. In his model, the rent externality is negative if inputs are weak complements or weak substitutes, and positive if inputs are asymmetric and strong complements or substitutes.[5] I extend Severinov's analysis further and demonstrate that the economic environment, and not only the technological environment, determines the magnitude of the rent externality. The rent externality could be negative, and maintaining a single CSO could be optimal, even under network substitutability, provided transfer payments are costly to society.

More generally, the present paper contributes to the literature on multi-contracting. Multi-contracting describes a situation where one or several principals contract with one or several agents. This is the first attempt, as far as I know, to analyze the welfare implications of changing the number of principals (here: regulators) as well as the number of agents (here: system operators) in a unified framework. Starting from a situation with multiple regulators and system operators, centralizing regulation and system operation is socially optimal in case of balanced political power and network complementarities. Conversely, if a country with little to gain from market integration possesses a dominating influence over the common regulatory agency, it is better to fully decentralize regulation and split system operation than to maintain centralized regulation and system operation. The existing literature is more partial in addressing either the optimal number of agents assuming a single principal (see Armstrong and Sappington, 2007 for a survey), or analyzing the optimal number of principals assuming a single agent (see Martimort, 2007 for a survey of such common agency models).

[5] Severinov's (2008) result that splitting production between several agents can be optimal under complementarity relies more on asymmetry than strong complementarity. Under symmetry, as in the present model, a single agent is optimal no matter the degree of complementarity.

2 The Model

Two countries, indexed by $i \neq j = \{1, 2\}$, distribute energy through interconnected national transmission networks. The union of the two national networks defines the common network. Interconnection enables energy trade between the two countries. Denote by S_i^I the sum of producer and consumer surplus in country i if the common network runs at full capacity - the market is *integrated* - and by S_i^A if the common network operates at reduced capacity. Market integration is beneficial to both countries, $S_i = S_i^I - S_i^A > 0$, $i = 1, 2$, but the gains from trade might be asymmetrically distributed: $S_1 \neq S_2$ in general. Apart from the standard gains from trade, both countries benefit from integration if competition is improved. Second, improved network capacity leads to a better utilization of total generation capacity and therefore lower aggregate production costs. Both countries benefit if these cost reductions are evenly distributed across the countries.

Total network reliability equals the probability $P(q)$ that the common network runs at full capacity and depends on the quality $q = (q_1, q_2)$ of the national networks. Total network reliability is a symmetric, twice continuously differentiable, increasing and concave function of quality: $\infty > P_i' > 0$, $P_{ii}'' < 0$, $P_{11}''P_{22}'' \geq P_{12}''P_{21}''$ for all $q \geq 0$, where $P_i' = \partial P/\partial q_i$, $P_{ii}'' = \partial^2 P/\partial q_i^2$ and $P_{ij}'' = \partial^2 P/\partial q_i \partial q_j$. As we shall later see, optimal network governance depends on the technological characteristics of the network. Specifically, the common network displays *complementarities* if the marginal effect on network reliability of increasing the quality of the domestic network is increasing in the quality of the foreign network: $P_{12}'' > 0$ and $P_{21}'' > 0$. If, instead, the marginal effect on network reliability of increasing the quality of the domestic network is decreasing in the quality of the foreign network, $P_{12}'' < 0$ and $P_{21}'' < 0$, there is network *substitutability*.

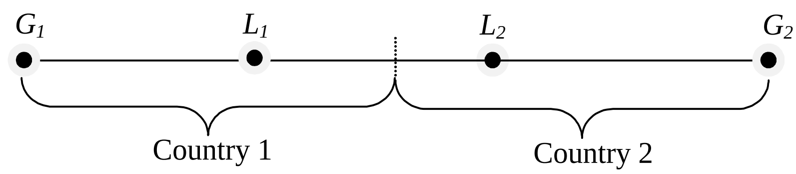

Figure 1: A simple radial network

Network characteristics are related to the topology of the network. Figure 1 depicts a very simple radial network. Energy flows in the radial network from production (generation) nodes G_1 in country 1, and G_2 in country 2, to consumption (load) nodes L_1 in country 1, and L_2 in country 2, through a line of mutually important interconnections. Seasonal variation in consumption and production implies that production at G_1 sometimes is used to cover consumption at L_2, while production at G_2 at other times is used to cover consumption at L_1. Due to mutual dependence, the weakest link defines total network reliability. In the radial network, total network reliability equals the probability that both national networks run at full capacity. Let p_i be the reliability of network i. Under the simplifying assumption that network failures are stochastically independent across the two countries, i.e. $p_i = p(q_i)$, total reliability of this radial network is given by $P(q) = p(q_1)p(q_2)$, with $P''_{12} = P''_{21} = p'(q_1)p'(q_2) > 0$. The radial network thus displays network complementarity.

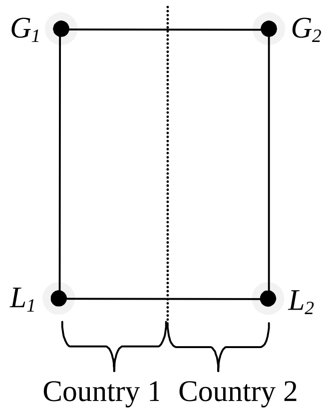

Figure 2: A simple meshed network

Figure 2 illustrates a simple meshed network. In a meshed network, energy flows from production nodes G_1 and G_2 to consumption nodes L_1 and L_2 through a web of interconnected and mutually substitutable transmission lines. Consumption at L_1 can be served entirely through the direct interconnection from G_1 or transited via country 2. The same is true for consumption at L_2 in country 2. Assuming that only one of the transmission lines is necessary to serve the entire market and that network failures are stochastically independent across countries, total reliability of this meshed network equals the probability that at least one national network runs at full capacity, i.e. $P(q) = 1 - (1 - p(q_1))(1 - p(q_2))$, with $P''_{12} = P''_{21} = -p'(q_1)p'(q_2) < 0$. The meshed network displays a high degree of substitutability.[6,7]

Network quality in country i is the product of exogenous productivity $\beta_i \in \{\underline{\beta}, \overline{\beta}\}$ of network i and the resources $m_i \geq 0$ spent on maintaining network i: $q_i = \beta_i m_i$, $i = 1, 2$. Productivity in network i is low ($\beta_i = \underline{\beta} > 0$) with probability $1 - v$ and high ($\beta_i = \overline{\beta} > \underline{\beta}$) with probability v. With this (common knowledge) stochastic structure, total productivity $\beta = (\beta_1, \beta_2)$ is stochastically independent across the two networks. Productivity differences arise due to

[6] In fact, the different parts of the network are perfect substitutes under the additional assumption that network failures are exponentially distributed: $p(q_i) = 1 - \exp\{-\gamma q_i\}$ implies $P(q) = 1 - \exp\{-\gamma(q_1 + q_2)\}$. Note also the implicit assumption in Figure 2 that the interconnectors between G_1 and G_2 respective L_1 and L_2 are always available.

[7] Real transmission networks are vastly more complex than the simple ones depicted in the two figures, with some parts of the network being substitutes while other parts are complements. Despite the complex topology of transmission networks, standard economic tests can sometimes be applied to evaluate the relationship between different interconnections. PJM covers the northeastern parts of the USA and is one of the world's largest electricity markets. As a part of the market optimization procedure, the system operator calculates the hourly shadow price on capacity utilization of every transmission line. In PJM, two transmission line are substitutes (complements) if capacity utilization on one line is increasing (decreasing) in the shadow price of the other line.

differences in weather conditions, geography, or other factors. For instance, it is necessary to trim the vegetation to keep a safety margin between transmission lines and trees. The adequate amount of trimming depends on exogenous vegetation growth. While it may be possible to gauge the maintenance requirements for specific parts of the network, the full grid is so complex that detailed system knowledge is required to asses overall productivity. To capture incomplete information, I assume that the regulator knows only the stochastic properties of β.

The system operator receives a transfer t_i for managing network i. Maintenance m_i includes the tangible resources (labour and capital) the system operator effectively spends on improving the quality of the network as well as the intangible efforts the organization devotes to identifying the strengths and weaknesses of the grid, devising efficient organizational procedures and optimizing the reliability rules. Presumably, the organization prefers to spend some of its resources on other things than maintenance, for example profit-sharing, bonuses, excessive wages and fringe benefits. Moreover, organizational effort is probably costly to management and employees. I therefore assume that the system operator faces a positive maintenance cost $\psi(m_i)$, which is three times continuously differentiable, increasing and convex: $\psi'(0) = 0$, $\psi'' > 0$ and $\psi''' \geq 0$. The regulator would have to engage in costly audits, thorough examinations of the operational procedures and system requirements to get a clear picture of maintenance spending m_i. To capture costly monitoring, I assume m_i to be unobservable to the regulator in the absence of a performance-based regulation designed to shape maintenance incentives. It follows that even operator rent $u_i = t_i - \psi(m_i)$ is directly unobservable. With this specification, the system operator has an incentive to maximize transfers and minimize maintenance.[8]

Although neither of the two *input* components β_i and m_i are publicly observable, there usually exist contractible *output* measures which provide information about network quality q_i. Under stochastic independence, for example, the reliability p_i of network i is an equivalent measure of network quality: $q_i = p^{-1}(p_i)$. To capture imperfect monitoring while keeping matters simple, I assume that quality q_i is directly observable and contractible.

Ex post social welfare equals the expected aggregate gains from trade plus operator rent minus the social cost of transfers:

$$P(q)(S_1 + S_2) + \sum_{i=1,2}(u_i - (1 + \lambda)t_i),$$

where $\lambda > 0$ is the shadow price of public funds and the same in both countries. Regulation here affects the expected gains of trade only through its effect on network reliability P. There is no reason why network governance should have any direct effect on the gains of trade S_1 and S_2. If operator revenues accrued from user fees or congestion rents, instead of being tax financed transfers as in the present model, regulation would have a direct effect on the gains from trade.[9]

[8] Operator rent can be viewed as a reduced form of the following maximization problem: Assume that NSO i spends $l_i \geq 0$ on "leasurely activities" and $m_i \geq 0$ on maintenance to maximize quasi-linear utility $v(l_i, m_i) = l_i + z(m_i)$, subject to the budget constraint $l_i + m_i \leq t_i$, and where $z(m_i) = m_i - \psi(m_i)$. The budget constraint is binding, so $u_i = v(t_i - m_i, m_i) = t_i - \psi(m_i)$.

[9] Introducing user fees or congestion rents would complicate the analysis technically without adding much in terms of qualitative insights. The difference between the two approaches is that the shadow price on usage fees or congestion rent is endogenously determined, whereas the shadow price λ is economy-wide and exogenous in

The timing is as follows: Nature draws β. NSO i learns β_i, but does not know more about β_j than the regulator(s). The CSO learns the entire productivity vector β. The regulator(s) commit(s) to direct regulatory contract(s), which consist of a regulatory policy $\mathbf{q}_i = (\overline{q}_i, \widehat{q}_i, \widetilde{q}_i, \underline{q}_i)$ and a transfer policy $\mathbf{t}_i = (\overline{t}_i, \widehat{t}_i, \widetilde{t}_i, \underline{t}_i)$ for each network $i = 1, 2$. Upon observing the regulatory contracts $(\mathbf{q}_1, \mathbf{t}_1)$ and $(\mathbf{q}_2, \mathbf{t}_2)$, each NSO, alternatively the CSO, decides whether to accept the regulatory contract or refuse it.[10] A system operator who turns down the contract receives reservation utility 0. If they both accept (I assume that this is always socially optimal), the regulated quality of network i is $\overline{q}_i$ and the associated transfer to network i is $\overline{t}_i$ if both networks report high productivity, and $\underline{q}_i$ versus $\underline{t}_i$ if they both report low productivity. In case of dissimilar productivity reports ($\beta_i = \overline{\beta} > \underline{\beta} = \beta_j$), the quality/transfer pair equals $(\widehat{q}_i, \widehat{t}_i)$ for the high productivity network, and $(\widetilde{q}_j, \widetilde{t}_j)$ for the low productivity network. Regulation is transparent: The set of regulatory contracts as well as the productivity reports of the NSOs are common knowledge.[11] Transparency simplifies the analysis and allows me to emphasize the welfare effects associated with different network structures, thus eliminating effects stemming from ad hoc restrictions in the set of enforceable contracts.

The incentive contracts considered here are far more complex than the simple regulatory contracts we see in reality. Comparing network structures under the assumption of optimal regulatory policies under each respective structure allows me to isolate the effects of network governance on welfare. A comparison of network governance under simpler, suboptimal regulatory schemes runs the risk of confusing governance effects with the effects of inadequately designed regulatory policies.

Using $m_i = q_i/\beta_i$ and $t_i = u_i + \psi(m_i)$, I can write expected national welfare in country $i = 1, 2$ entirely in terms of (observable) quality $\mathbf{Q} = (\mathbf{q}_1, \mathbf{q}_2)$ and (unobservable) operator rent $\mathbf{u}_i = (\overline{u}_i, \widehat{u}_i, \widetilde{u}_i, \underline{u}_i)$:

$$\begin{aligned} W_i(\mathbf{Q}, \mathbf{u}_i) = {} & v^2[P(\overline{q}_1, \overline{q}_2)S_i - (1+\lambda)\psi(\overline{q}_i/\overline{\beta}) - \lambda\overline{u}_i] \\ & + v(1-v)[(P(\widehat{q}_1, \widetilde{q}_2) + P(\widetilde{q}_1, \widehat{q}_2))S_i - (1+\lambda)(\psi(\widehat{q}_i/\overline{\beta}) + \psi(\widetilde{q}_i/\underline{\beta})) - \lambda(\widehat{u}_i + \widetilde{u}_i)] \\ & + (1-v)^2[P(\underline{q}_1, \underline{q}_2)S_i - (1+\lambda)\psi(\underline{q}_i/\underline{\beta}) - \lambda\underline{u}_i]. \end{aligned} \tag{1}$$

The fundamental trade-off in this model is between network reliability and maintenance cost. However, the surplus function $P(q)S_i$ is a special case of a more general surplus function $V_i(q)$, where q denotes transmission capacity. The crucial assumptions in the model are that capacity expansions are costly, capacity changes have effects on welfare in both regions, and there could

the current setup. See Chapter 2 in Laffont and Tirole (1993) for an analysis of the analogy between tax-based regulation and revenue-based regulation.

[10] With the timing of this model, contracting takes place under asymmetric information. It is always debatable whether the agent has all relevant information about its own productivity at the contracting stage. However, it is probably realistic to assume that the agent can shut down at any time production becomes unprofitable. With such an interim participation constraint, the analysis would be similar to the one presented here even if agents did not possess all relevant information at the contracting stage.

[11] Combes et al. (1997) endogenize this choice and show that transparent regulation welfare dominates non-transparent regulation in a Cournot model of regulated trade. It is still an open research question whether the optimality of transparency extends to the case of strategic complementarities. Note also that the European Commission (2007) views transparency as essential for a properly working market.

be strategic interaction between regions in the decision to expand capacity. If m_i is investment and $\psi(\cdot)$ is the real investment cost, the qualitative results of this paper can be used to draw conclusions about the regulation of transmission investments in an integrated market.

3 Equilibrium policies

To highlight the importance of network structure, I evaluate expected welfare and the optimal policies under the various structures against the first-best, complete information solution. Under complete information about productivity and for any regulatory policy, it is optimal to set operator rent as low as possible since transfer payments are costly to society. System operation is voluntary. With an outside option equal to zero, the minimal transfers are at the point at which system operation is just profitable: $\mathbf{u}_1 = \mathbf{u}_2 = \mathbf{0}$. To ensure the existence of an optimum, I employ a boundary condition:

$$\text{For } i \neq j = 1,2,\ \exists k > 0 \text{ such that } P_i'(q)(S_1 + S_2) < (1+\lambda)\psi'(q_i/\overline{\beta})/\overline{\beta}\ \forall q_i > k,\ \forall q_j \geq 0 \quad (2)$$

throughout the analysis. This boundary condition is satisfied if the marginal maintenance cost goes to infinity, or if marginal network reliability goes to zero as maintenance spending goes to infinity. Straightforward maximization of aggregate welfare $W_1(\mathbf{Q}, \mathbf{0}) + W_2(\mathbf{Q}, \mathbf{0})$ over $\mathbf{Q}$ yields:

Lemma 1 *The first-best policy is unique and symmetric,* $\mathbf{q}_1^{fb} = \mathbf{q}_2^{fb} = \mathbf{q}^{fb} = (\overline{q}^{fb}, \widehat{q}^{fb}, \widetilde{q}^{fb}, \underline{q}^{fb})$, *and characterized by:*

$$\begin{aligned} P_1'(\overline{q}^{fb}, \overline{q}^{fb})(S_1 + S_2) = &\quad (1+\lambda)\psi'(\overline{q}^{fb}/\overline{\beta}))/\overline{\beta} \\ P_1'(\widehat{q}^{fb}, \widetilde{q}^{fb})(S_1 + S_2) = &\quad (1+\lambda)\psi'(\widehat{q}^{fb}/\overline{\beta}))/\overline{\beta} \\ P_1'(\widetilde{q}^{fb}, \widehat{q}^{fb})(S_1 + S_2) = &\quad (1+\lambda)\psi'(\widetilde{q}^{fb}/\underline{\beta}))/\underline{\beta} \\ P_1'(\underline{q}^{fb}, \underline{q}^{fb})(S_1 + S_2) = &\quad (1+\lambda)(\psi'(\underline{q}^{fb}/\underline{\beta}))/\underline{\beta}. \end{aligned} \quad (3)$$

Under network complementarity, $\overline{q}^{fb} > \widehat{q}^{fb}$ *and* $\widetilde{q}^{fb} > \underline{q}^{fb}$, *whereas* $\widehat{q}^{fb} > \overline{q}^{fb}$ *and* $\underline{q}^{fb} > \widetilde{q}^{fb}$ *under network substitutability.*

The proof is in the Appendix.

The first-best policy arises at the point at which the marginal benefit of network reliability equals the marginal social maintenance cost. Network reliability is a public good: The value of network reliability depends on the aggregate gains from trade. Therefore, the optimal policy is symmetric, although the gains from energy market integration may be asymmetrically distributed across countries ($S_1 \neq S_2$). The optimal distribution of maintenance spending across the network occurs at the point at which the marginal rate of substitution equals the marginal rate of technical substitution. In a network with asymmetric productivity ($\beta_1 = \overline{\beta} > \underline{\beta} = \beta_2$):

$$\frac{\overline{\beta} P_1'(\widehat{q}^{fb},\widetilde{q}^{fb})}{\underline{\beta} P_2'(\widehat{q}^{fb},\widetilde{q}^{fb})} = \frac{\psi'(\widehat{q}^{fb}/\overline{\beta})}{\psi'(\widetilde{q}^{fb}/\underline{\beta})},$$

which is independent of the gains from trade.

Quality varies less with productivity across the networks under network complementarity than substitutability. Under complementarity, a productivity increase leads to higher quality in all parts of the network. Under substitutability, higher productivity in one part of the network leads to lower quality in the other.

From an inspection of the conditions for optimal network quality, one might be tempted to conclude that larger gains from trade would always yield more network maintenance. This is not necessarily true. Under network substitutability, more maintenance in one part of the network has the effect of depressing the marginal benefit of maintenance in the other. In principle, this substitution effect could dominate the direct "income" effect, rendering network quality an inferior good. I consider here the case where network quality is a normal good in the sense that an increase in the aggregate gains from trade leads to higher maintenance spending in all parts of the network under first-best regulation. A sufficient condition on network reliability is that the degree of substitutability between q_i and q_j is sufficiently weak (stated here without proof):

$$-P_{ij}'' \leq |P_{jj}''| P_i'/P_j' \text{ for all } q \geq 0,\ i \neq j = 1, 2. \tag{4}$$

In this case the direct effect dominates the substitution effect. Condition (4) is not particularly restrictive. It is always satisfied under quality complementarity ($P_{ij}'' \geq 0$) and even under perfect substitutability (i.e. $P(q) = p(q_1 + q_2)$). For simplicity, I assume throughout the analysis that condition (4) holds.

Under complete information it does not matter whether there is a common system operator (CSO) or two national system operators (NSOs). In this model, a CSO spending m_1 and m_2 on maintenance in the two parts of the networks incurs the same maintenance cost $\psi(m_1) + \psi(m_2)$ as two NSOs spending m_1 and m_2 in their respective networks. Maintenance economies of scale would favour the creation of a single CSO under complete information, whereas two NSOs would be better under diseconomies of scale. The present paper emphasizes the effects of political constraints and incentives on optimal network structure. Therefore, I have not signed cost advantages in any direction.

3.1 Separation

Separation constitutes the most decentralized governance structure whereby a national regulatory agency (NRA) in each country has the responsibility for regulating the performance of a national system operator (NSO). I restrict attention to *dominant strategy implementable direct (DSID)* contracts; no NSO can strictly benefit from misrepresenting its productivity, nor shutting down, no matter what the other NSO reports. Under dominant strategy implementation, regulatory policies are robust to collusive coordination among the NSOs, and to any misconceptions either system operator might have about the actions of the other. A multi-principal Revelation Principle applies to this analysis: Every equilibrium of a dominant strategy regulation game with a more general message space can equivalently be represented as the equilibrium of a game in which both regulators have committed to offering DSID mechanisms; see the Appendix.

By transparency, NRA i can condition the regulatory policy on the productivity reports of both NSOs. NRA i benefits from conditioning regulation on both reports in spite of stochastic independence of information because total network reliability depends on quality in both parts of the network. Any contract accepted by the NSO in country $i = 1, 2$ must first satisfy the participation constraint

$$\mathbf{u}_i \geq \mathbf{0}, \tag{5}$$

whereby it is required that system operation always be profitable, no matter the system operator's own productivity nor its subjective belief about the productivity report of the other.

Because of asymmetric information, NRA i cannot observe whether network quality q_i is low for exogenous reasons (low productivity) or endogenous reasons (poor maintenance). If NSO i is of high productivity, it can always secure itself a positive rent by understating productivity, as it must spend comparatively little, $q_i/\overline{\beta}$ versus $q_i/\underline{\beta}$, on maintenance to reach quality level q_i. To maintain incentive compatibility, the regulator must pay the high productivity NSO sufficient transfers that it cannot benefit from understating productivity:

$$\begin{aligned} \overline{u}_i &\geq \widetilde{u}_i + \psi(\widetilde{q}_i/\underline{\beta}) - \psi(\widetilde{q}_i/\overline{\beta}) = \widetilde{u}_i + \Phi(\widetilde{q}_i) \\ \widehat{u}_i &\geq \underline{u}_i + \psi(\underline{q}_i/\underline{\beta}) - \psi(\underline{q}_i/\overline{\beta}) = \underline{u}_i + \Phi(\underline{q}_i). \end{aligned} \tag{6}$$

The value of private information, the *informational rent*, is precisely the cost differential $\Phi(q_i)$ above. It is increasing and convex ($\Phi'(0) = 0$, $\Phi'' > 0$) owing to decreasing returns to maintenance spending ($\psi'' > 0$, $\psi''' \geq 0$). The second requirement of incentive compatibility is that the low productivity NSO is always better off reporting its true productivity than overstating it to $\overline{\beta}$:

$$\widetilde{u}_i \geq \overline{u}_i - \Phi(\overline{q}_i),\ \underline{u}_i \geq \widehat{u}_i - \Phi(\widehat{q}_i). \tag{7}$$

The regulator in country i chooses the policy $(\mathbf{q}_i, \mathbf{u}_i)$ to maximize expected national welfare $W_i(\mathbf{Q}, \mathbf{u}_i)$ subject to the above participation and incentive constraints, taking the policy $(\mathbf{q}_j, \mathbf{u}_j)$ in the other country as given. The contracts $(\mathbf{q}_1^S, \mathbf{u}_1^S)$ and $(\mathbf{q}_2^S, \mathbf{u}_2^S)$ constitute a Nash Equilibrium under Separation if each contract is DSID and no regulator can raise national welfare by a unilateral deviation to another DSID contract. By standard arguments, see e.g. Chapter 1 in Laffont and Tirole (1993), the DSID constraints can be replaced by a binding participation constraint for the low type ($\widetilde{u}_i = \underline{u}_i = 0$), binding downward incentive constraints (6), and the monotonicity constraint

$$\overline{q}_i \geq \widetilde{q}_i,\ \widehat{q}_i \geq \underline{q}_i. \tag{8}$$

Substituting $\mathbf{u}_i = (\Phi(\widetilde{q}_i), \Phi(\underline{q}_i), 0, 0)$ into (1), I can write national welfare under Separation entirely in terms of quality $\mathbf{Q}$:

$$\begin{aligned} W_i^S(\mathbf{Q}) &= v^2[P(\overline{q}_1,\overline{q}_2)S_i-(1+\lambda)\psi(\overline{q}_i/\overline{\beta})] \\ &+v(1-v)[(P(\widehat{q}_1,\widetilde{q}_2)+P(\widetilde{q}_1,\widehat{q}_2))S_i-(1+\lambda)(\psi(\widehat{q}_i/\overline{\beta})+\psi(\widetilde{q}_i/\underline{\beta})+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi(\widetilde{q}_i))] \\ &+(1-v)^2[P(\underline{q}_1,\underline{q}_2)S_i-(1+\lambda)(\psi(\underline{q}_i/\underline{\beta})+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi(\underline{q}_i))]. \end{aligned} \tag{9}$$

Lemma 2 *There exists a unique equilibrium* $\mathbf{Q}^S=(\mathbf{q}_1^S,\mathbf{q}_2^S)$ *under Separation (for generic parameter values), where* $\mathbf{q}_1^S=(\overline{q}_1^S,\widehat{q}_1^S,\widetilde{q}_1^S,\underline{q}_1^S)$ *is characterized by*

$$\begin{aligned} P_1'(\overline{q}_1^S,\overline{q}_2^S)S_1 &= (1+\lambda)\psi'(\overline{q}_1^S/\overline{\beta})/\overline{\beta} \\ P_1'(\widehat{q}_1^S,\widetilde{q}_2^S)S_1 &= (1+\lambda)\psi'(\widehat{q}_1^S/\overline{\beta})/\overline{\beta} \\ P_1'(\widetilde{q}_1^S,\widehat{q}_2^S)S_1 &= (1+\lambda)(\psi'(\widetilde{q}_1^S/\underline{\beta})/\underline{\beta}+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi'(\widetilde{q}_1^S)) \\ P_1'(\underline{q}_1^S,\underline{q}_2^S)S_1 &= (1+\lambda)(\psi'(\underline{q}_1^S/\underline{\beta})/\underline{\beta}+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi'(\underline{q}_1^S)), \end{aligned} \tag{10}$$

and analogously for $\mathbf{q}_2^S=(\overline{q}_2^S,\widehat{q}_2^S,\widetilde{q}_2^S,\underline{q}_2^S)$. *Total network reliability is too low relative to the first-best policy, but the country with the largest gains from energy market integration spends too much on maintenance relative to the other.*

The proof is in the Appendix.

The equilibrium policies $\mathbf{q}_1^S$ and $\mathbf{q}_2^S$ deviate from the first-best solution $\mathbf{q}^{fb}$ in three respects, two of which have to do with the non-cooperative manner in which the regulatory policies are set under Separation. Network reliability is a public good. By failing to take into account the positive externality of increased network reliability, the national system operators spend too little on maintenance: The full marginal effect is $P_i'(q)(S_1+S_2)$, whereas NRA i only cares about $P_i'(q)S_i$.

Second, the regulatory policies suffer from productive inefficiencies. The distribution of maintenance spending is given by

$$\frac{\overline{\beta}P_1'(\widehat{q}_1^S,\widetilde{q}_2^S)S_1}{\underline{\beta}P_2'(\widehat{q}_1^S,\widetilde{q}_2^S)S_2}=\frac{\psi'(\widehat{q}_1^S/\overline{\beta})}{\psi'(\widetilde{q}_2^S/\underline{\beta})+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\underline{\beta}\Phi'(\widetilde{q}_2^S)}$$

when the two networks are asymmetric ($\beta_1=\overline{\beta}>\beta_2=\underline{\beta}$). With asymmetric gains from trade (say, $S_1>S_2$), the high-productivity network tends to spend comparatively more on maintenance because the perceived relative marginal benefit of network reliability is too high.

Third, maintenance under-spending is exacerbated by the presence of asymmetric information. Suppose the regulator wants to increase maintenance spending in the low productivity NSO, e.g. raise $\widetilde{q}_i$ marginally. To preserve the profitability of system operation, the regulator must increase the transfers to the low productivity NSOs in proportion to the extra maintenance cost. Since transfers are costly, the marginal social maintenance cost is $(1+\lambda)\psi'(\widetilde{q}_i/\underline{\beta})/\underline{\beta}$. Under asymmetric information, *all* types of NSOs benefit from more high-powered incentives because the regulator cannot ex ante target transfers to low productivity NSOs. To preserve incentive compatibility, the regulator must also compensate the high productivity NSO by awarding it additional transfers. This spill-over effect, the informational rent, leads to a *virtual marginal maintenance cost*

$$(1+\lambda)(\psi'(\widetilde{q}_i/\underline{\beta})/\underline{\beta} + \frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi'(\widetilde{q}_i))$$

which is higher than the marginal social maintenance cost. Under asymmetric information, optimal maintenance spending is found at the point at which the marginal benefit of network reliability equals the virtual marginal maintenance cost. The higher is the shadow price λ of public funds, the higher is the probability v that the NSO is of a high productivity and the stronger is the cost advantage of the high productivity NSO (the higher is Φ'), the higher is the virtual marginal maintenance cost and the lower is equilibrium maintenance spending.

Brainard and Martimort (1996) analyze a multi-principal, multi-agent game with some similarities to the game above. In a game of strategic trade policy under asymmetric information, each government offers the home firm a production subsidy to compete with an equally subsidized foreign firm in a third country market. Under the assumption that each government maximizes the domestic firm's rent (less the social cost of the subsidy), production subsidies are excessive because product market competition locks the two governments in a prisoner's dilemma. Asymmetric information serves to reduce policy distortions by increasing the virtual marginal cost of production subsidies. In the present context, the fundamental coordination problem stems from free riding on a public good (network reliability), not competition. The focus is on aggregate welfare (including consumer's surplus) and not on firm rent. Consequently, production subsidies are too small, and asymmetric information only aggravates the problem. Another difference is that Brainard and Martimort (1996) restrict attention to the symmetric case and therefore do not address productive inefficiencies stemming from asymmetric gains from trade.[12]

But how serious is the agency problem, really? There are two crucial ingredients that make up an agency problem. First, the agent must have an *incentive* to distort maintenance. In this model, the incentive arises from the assumption that efficient maintenance strains the organization in a way that its members perceive as costly and/or there are private benefits of alternative spending. It does not matter whether income is in the form of congestion rent, user fees or government transfers. Also, it does not matter whether the NSO is private or state-owned. A privately owned NSO would cut down on maintenance to deliver profit, whereas a state-owned NSO would reduce maintenance to increase managerial compensation, fringe benefits, etc. If there were no misaligned incentives, the regulator could simply rely on voluntary reliability standards and compensate the NSOs just enough that they break even. The second key ingredient

[12] Analyzing asymmetries is difficult in their setting because their model features a continuum of types. Characterizing asymmetric equilibria then amounts to finding the solution to a pair of asymmetric differential equations. Introducing asymmetries is straightforward in a discrete type space. Importantly, a multiplicity of equilibria complicates their welfare analysis, whereas the present model admits a unique equilibrium.

of the agency problem is that the agent possesses private information about network reliability and maintenance, and therefore has the *possibility* of distorting maintenance. If there were misaligned incentives, but no informational asymmetries, the regulator could simply order the optimal amount of maintenance and compensate the system operator accordingly. The presence of an agency problem implies instead that the regulator optimally engages in performance-based regulation. One of the best-known examples of performance-based regulation is the *RPI-X* scheme used by Ofgem, whereby network companies are rewarded/penalized on the basis of an output measure which explicitly includes network reliability and availability. From 2013 onwards Ofgem plans to introduce the so-called *RIIO* model which rewards networks even on the basis of innovation (Ofgem, 2010). In reality, regulators (at least some of them) seem to be concerned with incentive problems among the network companies.

3.2 Common regulation

Asymmetric gains from energy market integration ($S_1 \neq S_2$) imply that the two national regulatory agencies (NRAs) choose different policies under Separation ($\mathbf{q}_1^S \neq \mathbf{q}_2^S$). Under Common regulation, the regulatory responsibility is collected in the hands of a common regulatory agency (CRA). Yet, conflict over the optimal regulatory policy is *not* likely to vanish with the introduction of a common regulatory agency if the asymmetric gains from trade also remain under Common regulation. The desirability of Common regulation then depends on how the preferences of the different countries are aligned within the CRA. The simplest way of introducing political conflict is to assume that the CRA maximizes a weighted average of national welfare

$$\mu_1 W_1(\mathbf{Q}, \mathbf{u}_1) + \mu_2 W_2(\mathbf{Q}, \mathbf{u}_2),\ (\mu_1, \mu_2) \geq \mathbf{0},\ \mu_1 + \mu_2 = 1.$$

A relevant special case of this representation is majority voting, whereby whoever holds the majority in the board of directors exercises dictatorial powers over the design of the regulation ($\mu_i = 1$ if country i is in majority).

This seemingly innocuous representation carries the seeds of severe political exploitation. The common regulatory agency has the powers to tax the inhabitants in both countries, in order to finance system operation. This fiscal (tax) integration is not necessarily followed by corresponding political integration. Under simple majority rule, the CRA tailors its policy to maximize welfare $W_i(\mathbf{Q}, \mathbf{u}_i)$ in the majority country i, independently of the consequences for welfare in the minority country j. With a perceived shadow price of public funds equal to zero in country j, the CRA would profit from collecting excessive transfers from country j, in order to finance NSO i's system operation.[13] A first effort to curb exploitation would be a *proportionality rule*, requiring transfers to stand in proportion to the cost of system operation in the country where the transfers are collected. Yet, proportionality is not enough. Under simple majority rule, the majority has an incentive to overinvest in the minority network and finance it by means

[13] The problem of reconciling political and fiscal integration may explain why it has been so difficult to devise transfer rules for cross-border investments.

of local transfers. Increased network reliability benefits the majority, but the perceived shadow price on transfers is zero ($\partial W_i/\partial \mathbf{q}_j > 0$). This problem of excessive network investment is relieved by the imposition of an additional *non-discrimination rule*, whereby regulatory policy is required to be a function only of the productivity of the networks and not allowed to depend on the country in which the network is located. In the present setting, non-discrimination implies symmetric regulatory policies: $\mathbf{q}_1 = \mathbf{q}_2 = \mathbf{q} = (\overline{q}, \widehat{q}, \widetilde{q}, \underline{q})$ and $\mathbf{u}_1 = \mathbf{u}_2 = \mathbf{u} = (\overline{u}, \widehat{u}, \widetilde{u}, \underline{u})$. Conversely, symmetry implies non-discrimination and proportionality.[14]

Under proportionality and non-discrimination, the CRA sets $\mathbf{q}$ and $\mathbf{u}$ to maximize $\mu_1 W_1(\mathbf{q}, \mathbf{q}, \mathbf{u}) + \mu_2 W_2(\mathbf{q}, \mathbf{q}, \mathbf{u})$ subject to the participation constraint

$$\mathbf{u} \geq 0, \tag{11}$$

and incentive compatibility constraints

$$\overline{u} \geq \widetilde{u} + \Phi(\widetilde{q}),\ \widehat{u} \geq \underline{u} + \Phi(\underline{q}), \tag{12}$$

$$\widetilde{u} \geq \overline{u} - \Phi(\overline{q}),\ \underline{u} \geq \widehat{u} - \Phi(\widehat{q}). \tag{13}$$

As under Separation, the relevant constraints are downward incentive compatibility (12), low-type participation ($\widetilde{u} = \underline{u} = 0$) and monotonicity

$$\overline{q} \geq \widetilde{q},\ \widehat{q} \geq \underline{q}. \tag{14}$$

Operator rent is minimized by extracting all surplus from the low type, while paying the high type precisely the informational rent. Substituting $\mathbf{u} = (\Phi(\widetilde{q}), \Phi(\underline{q}), 0, 0)$ into the symmetric weighted welfare function, I obtain the common regulatory agency's policy function

$$\begin{aligned} \Gamma^{Cr}(\mathbf{q}) = \;& v^2[P(\overline{q}, \overline{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)\psi(\overline{q}/\overline{\beta})] \\ +\;& v(1-v)[2P(\widehat{q}, \widetilde{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)(\psi(\widehat{q}/\overline{\beta}) + \psi(\widetilde{q}/\underline{\beta}) + \tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi(\widetilde{q}))] \\ +\;& (1-v)^2[P(\underline{q}, \underline{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)(\psi(\underline{q}/\underline{\beta}) + \tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi(\underline{q}))]. \end{aligned} \tag{15}$$

Maximizing $\Gamma^{Cr}(\mathbf{q})$ over $\mathbf{q}$ and subject to $\overline{q} \geq \widetilde{q}$ and $\widehat{q} \geq \underline{q}$ yields:

Lemma 3 *Under Common regulation, the unique symmetric optimal policy* $\mathbf{q}^{Cr} = (\overline{q}^{Cr}, \widehat{q}^{Cr}, \widetilde{q}^{Cr}, \underline{q}^{Cr})$

[14] Symmetry implies that the NSOs are treated the same ex ante because they are all offered the same menu of contracts to choose from. However, the NSOs are treated differently ex post if they select different contracts from one another.

is characterized by

$$\begin{aligned} 2P_1'(\overline{q}^{Cr},\overline{q}^{Cr})(\mu_1 S_1+\mu_2 S_2) = &\quad (1+\lambda)\psi'(\overline{q}^{Cr}/\overline{\beta})/\overline{\beta} \\ 2P_1'(\widehat{q}^{Cr},\widetilde{q}^{Cr})(\mu_1 S_1+\mu_2 S_2) = &\quad (1+\lambda)\psi'(\widehat{q}^{Cr}/\overline{\beta})/\overline{\beta} \\ 2P_1'(\widetilde{q}^{Cr},\widehat{q}^{Cr})(\mu_1 S_1+\mu_2 S_2) = &\quad (1+\lambda)(\psi'(\widetilde{q}^{Cr}/\underline{\beta})/\underline{\beta}+\tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi'(\widetilde{q}^{Cr})) \\ 2P_1'(\underline{q}^{Cr},\underline{q}^{Cr})(\mu_1 S_1+\mu_2 S_2) = &\quad (1+\lambda)(\psi'(\underline{q}^{Cr}/\underline{\beta})/\underline{\beta}+\tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi'(\underline{q}^{Cr})). \end{aligned} \tag{16}$$

Network quality increases the more weight is placed on the national welfare of the country with the largest gains from trade ($\partial\mathbf{q}^{Cr}/\partial\mu_i > \mathbf{0}$ if $S_i > S_j$).[15]

The proof is in the Appendix.

Concentrating regulatory responsibility in the hands of a single regulatory agency gets rid of the productive inefficiency because maintenance spending is now optimally distributed throughout the network. With asymmetric network productivity ($\beta_1 = \overline{\beta} > \beta_2 = \underline{\beta}$):

$$\frac{\overline{\beta}}{\underline{\beta}}\frac{P_1'(\widehat{q}^{Cr},\widetilde{q}^{Cr})}{P_2'(\widehat{q}^{Cr},\widetilde{q}^{Cr})} = \frac{\psi'(\widehat{q}^{Cr}/\overline{\beta})}{\psi'(\widetilde{q}^{Cr}/\underline{\beta})+\frac{v}{1-v}\frac{\lambda}{1+\lambda}\underline{\beta}\Phi'(\widetilde{q}^{Cr})},$$

which is independent of the distribution (μ_1,μ_2) of political power. Establishing a common regulatory agency has no bearing on the agency problem. The incentive distortion persists, and the marginal rate of substitution equals the virtual marginal technical rate of substitution.

Common regulation can lead to over- or under-spending depending on the distribution of political power. For example, maintenance spending is excessive even compared to the first-best policy ($\mathbf{q}^{Cr} > \mathbf{q}^{fb}$) if the country with the most to gain from integration ($S_i > S_j$) has majority power ($\mu_i = 1$), and the social cost of transfers (λv) is low. In this case, the centralized regulator exaggerates the perceived benefit of increased network reliability.

3.3 Integration

Integration corresponds to the case of full centralization. System operation is concentrated in the hands of a common system operator (CSO) managing the entire network, and regulated by a common regulatory agency (CRA). To emphasize the effect of network structure, I assume sub-cost observability: The regulator observes and can contract on q_1 and q_2 separately, even when there is a single system operator. If the regulator could base its contract only on a composite function of quality q, say total network reliability $P(q)$, Integration would be less

[15] The restriction to dominant strategy implementable direct (DSID) contracts is without loss of generality here. Optimality of direct contracts follows from the Revelation Principle. Under Bayesiean implementation, the downward-binding incentive constraint is $v\overline{u}+(1-v)\widehat{u} = v(\widetilde{u}+\Phi(\widetilde{q}))+(1-v)(\underline{u}+\Phi(\underline{q}))$, the low type's participation constraint is $v\widetilde{u}+(1-v)\underline{u} = 0$, and the monotonicity constraint is $v\Phi(\overline{q})+(1-v)\Phi(\widehat{q}) \geq v\Phi(\widetilde{q})+(1-v)\Phi(\underline{q})$. Substituting expected operator rent $v\Phi(\widetilde{q})+(1-v)\Phi(\underline{q})$ into the policy function and maximizing over $\mathbf{q}$ yields (16). The monotonicity constraint is satisfied by this solution because $\overline{q}^{Cr} > \widetilde{q}^{Cr}$ and $\widehat{q}^{Cr} > \underline{q}^{Cr}$. Hence, Bayesian and dominant strategy implementation yield exactly the same optimal policy; see Mookherjee and Reichelstein (1992) for more on this topic.

appealing because of a narrower span of enforceable contracts. I discuss the implications of sub-cost observability below; see also Laffont and Tirole (1993).

The regulatory problem under Integration is one of multi-dimensional asymmetric information. Any feasible contract must satisfy the participation constraint

$$u(\beta) = \sum_{i=1,2}[t_i(\beta) - \psi(q_i(\beta)/\beta_i)] \geq 0 \ \forall \beta \in \{\underline{\beta}, \overline{\beta}\}^2 \tag{17}$$

and the incentive compatibility constraint

$$u(\beta) \geq \sum_{i=1,2}[t_i(b) - \psi(q_i(b)/\beta_i)] \ \forall (b, \beta) \in \{\underline{\beta}, \overline{\beta}\}^4. \tag{18}$$

The CSO possesses an informational advantage over the two national system operators as the CSO (by assumption) holds private information about the productivity $\beta = (\beta_1, \beta_2)$ of the entire grid. Unlike the two NSOs, the CSO is able to coordinate the performance of the various parts of the grid to maximize informational rent (recall, the regulatory policies are in dominating strategies under Common regulation). Thus, the CSO has more *agency power* than the two NSOs. The advantage of having fewer system operators is cross-subsidization; it is only necessary to meet the aggregate profitability and incentive constraints of the CSO, rather than one for each individual NSO. These costs and benefits will be more apparent later. As under Common regulation, political conflict may yield incentives for transfer exploitation across countries. I therefore assume that contracts are required to be symmetric even under Integration.

Even here the main concern is the incentive of the CSO for understating the productivity of the network. Therefore, the feasibility constraints (17) and (18) can be replaced by the lowest type's participation constraint $\underline{u} = \widetilde{u} = 0$, the downward-binding incentive compatibility constraints

$$\begin{aligned} 2\overline{u} = &\ \max\{\widehat{u} + \widetilde{u} + \Phi(\widetilde{q}); 2\underline{u} + 2\Phi(\underline{q})\} \\ \widehat{u} + \widetilde{u} = &\ 2\underline{u} + \Phi(\underline{q}) \end{aligned}, \tag{19}$$

and the monotonicity constraint:

$$\min\{\overline{q}; \widehat{q}\} \geq \max\{\widetilde{q}; \underline{q}\}. \tag{20}$$

Substituting the binding constraints into the policy function $\mu_1 W_1(\mathbf{q}, \mathbf{q}, \mathbf{u}) + \mu_2 W_2(\mathbf{q}, \mathbf{q}, \mathbf{u})$, the CRA's problem reduces to maximizing

$$\begin{aligned} \Gamma^I(\mathbf{q}, \overline{u}) = &\ v^2[P(\overline{q}, \overline{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)\psi(\overline{q}/\overline{\beta})] - \lambda v^2 \overline{u} \\ + &\ v(1-v)[2P(\widehat{q}, \widetilde{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)(\psi(\widehat{q}/\overline{\beta}) + \psi(\widetilde{q}/\underline{\beta}))] \\ + &\ (1-v)^2[P(\underline{q}, \underline{q})(\mu_1 S_1 + \mu_2 S_2) - (1+\lambda)(\psi(\underline{q}/\underline{\beta}) + \tfrac{\lambda}{1+\lambda}\tfrac{v}{1-v}\Phi(\underline{q}))] \end{aligned} \tag{21}$$

over $\mathbf{q}$ and $\overline{u}$, subject to $2\overline{u} \geq \Phi(\underline{q}) + \max\{\Phi(\widetilde{q}); \Phi(\underline{q})\}$ and monotonicity (20):

Lemma 4 *The optimal symmetric policy* $\mathbf{q}^I = (\overline{q}^I, \widehat{q}^I, \widetilde{q}^I, \underline{q}^I)$ *under Integration is characterized* *by*

$$
\begin{aligned}
2P_1'(\overline{q}^I,\overline{q}^I)(\mu_1 S_1+\mu_2 S_2) &= (1+\lambda)\psi'(\overline{q}^I/\overline{\beta})/\overline{\beta}\\
2P_1'(\widehat{q}^I,\widetilde{q}^I)(\mu_1 S_1+\mu_2 S_2) &= (1+\lambda)\psi'(\widehat{q}^I/\overline{\beta})/\overline{\beta}\\
2P_1'(\widetilde{q}^I,\widehat{q}^I)(\mu_1 S_1+\mu_2 S_2) &= (1+\lambda)(\psi'(\widetilde{q}^I/\underline{\beta})/\underline{\beta}+\tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\tfrac{\widetilde{\xi}^I}{\lambda v^2}\Phi'(\widetilde{q}^I))\\
2P_1'(\underline{q}^I,\underline{q}^I)(\mu_1 S_1+\mu_2 S_2) &= (1+\lambda)(\psi'(\underline{q}^I/\underline{\beta})/\underline{\beta}+\tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}(1+\tfrac{\lambda v^2+2\underline{\xi}^I}{2\lambda v(1-v)})\Phi'(\underline{q}^I)) \qquad (22)\\
\widetilde{\xi}^I+\underline{\xi}^I &= \lambda v^2/2\\
\widetilde{\xi}^I(2\overline{u}^I-\Phi(\underline{q}^I)-\Phi(\widetilde{q}^I)) &= 0\\
\underline{\xi}^I(2\overline{u}^I-2\Phi(\underline{q}^I)) &= 0,
\end{aligned}
$$

where $\widetilde{\xi}^I \geq 0$ *and* $\underline{\xi}^I \geq 0$ *are the Kuhn-Tucker multipliers associated with* $2\overline{u}^I \geq \Phi(\underline{q}^I)+\Phi(\widetilde{q}^I)$ *and* $2\overline{u}^I \geq 2\Phi(\underline{q}^I)$*. Quality increases the more weight is placed on the national welfare of the country with the largest gains from trade (*$\partial \mathbf{q}^I/\partial\mu_i > \mathbf{0}$ *if* $S_i > S_j$*). Also,* $P(\widehat{q}^I,\widetilde{q}^I) > P(\widehat{q}^{Cr},\widetilde{q}^{Cr})$*, but* $P(\underline{q}^I,\underline{q}^I) < P(\underline{q}^{Cr},\underline{q}^{Cr})$*.*

The proof is in the Appendix.

The more political influence the country with the most to gain from market integration has, the higher is maintenance spending. This is the same as under Common regulation. Moreover, coordination yields productive efficiency, in the sense that total spending is optimally distributed across the network. However, productive efficiency depends crucially on the ability of the NRA to contract on q_1 and q_2, separately (or network reliability p_1 and p_2 in the case of stochastic independence of failures across the national networks). Suppose instead that the NRA can only contract on total network reliability P. This contractual incompleteness implies that the NRA is forced to delegate the distribution of maintenance spending to the CSO. If network productivity differs across the network ($\beta_1 = \overline{\beta} > \underline{\beta} = \beta_2$), the CSO's cost-minimizing choice of maintenance spending is characterized by:

$$
\frac{\overline{\beta}P_1'(\widehat{q}^I,\widetilde{q}^I)}{\underline{\beta}P_2'(\widehat{q}^I,\widetilde{q}^I)} = \frac{\psi'(\widehat{q}^I/\overline{\beta})}{\psi'(\widetilde{q}^I/\underline{\beta})} \geq \frac{\psi'(\widehat{q}^I/\overline{\beta})}{\psi'(\widetilde{q}^I/\underline{\beta})+\underline{\beta}\frac{v}{1-v}\frac{\lambda}{1+\lambda}\frac{\widetilde{\xi}^I}{\lambda v^2}\Phi'(\widetilde{q}^I)},\ P(\widehat{q}^I,\widetilde{q}^I) = P.
$$

Under delegation, the CSO fails to internalize the social cost of operator rent and therefore spends too much on maintenance in the low productivity part of the network compared to the second-best policy. Productive inefficiency stemming from delegation would render Integration less appealing from a welfare point of view.

Differences arise between Common regulation and Integration even in the absence of any delegation problems under Integration. Under Common regulation, two system operators independently strive to maximize their rent. Under Integration, a single system operator exercises agency power. The ability to jointly understate the performance of the common network (report $(\underline{\beta},\underline{\beta})$ when the true type is $(\overline{\beta},\overline{\beta})$) jacks up the virtual marginal maintenance cost of the least productive common network (of type $(\underline{\beta}, \underline{\beta})$), and reduces the virtual marginal maintenance cost of a common network with intermediate productivity ($\beta_i = \overline{\beta} > \underline{\beta} = \beta_j$).[16] Agency power thus yields more extreme incentives, with network reliability being less distorted in case of intermediate productivity and more distorted whenever the common network is of a uniformly low productivity.

4 Comparison of network structures

Which is the optimal number of regulatory agencies? National regulatory agencies (NRAs) provide insufficient incentives for maintenance by failing to internalize the full gains from market integration abroad. A lack of policy coordination among the NRAs further exacerbate the distortions, as the maintenance actually undertaken is suboptimally distributed across the network. Establishing a common regulatory agency (CRA) responsible for maintaining the entire network achieves the required coordination of maintenance spending. Yet, the desirability of a CRA depends not only on its ability to distribute maintenance spending optimally, but also on aggregate spending incentives. These incentives depend in turn on the balance of political power between the countries, represented in this model by (μ_1, μ_2). If the country that values integration the most exerts a dominant influence over the CRA (μ_i is high and $S_i > S_j$), over-spending tends to occur because the perceived gains from trade are exaggerated. Conversely, too much weight on the country that values energy integration the least (μ_j is high and $S_i > S_j$) leads to maintenance under-spending. Balanced maintenance incentives require balanced political influence:

Proposition 1 *Centralizing regulatory responsibility in the hands of a common regulatory agency (CRA) welfare dominates a decentralized system with national regulatory agencies (NRAs) if and only if the CRA is able to balance the political influence of the member countries (μ_i is sufficiently close to $1/2$). It is strictly better from a welfare perspective to maintain decentralization with two NRAs if political influence in the CRA is biased strongly in favour of a country with little to gain from market integration ($\mu_j \approx 1$ and $S_j \approx 0$).*

The proof is in the Appendix.

With an equal distribution of political influence, no country state can exert enough influence over the centralized regulatory policy to tilt it in one's own favour; in fact, the CRA maximizes aggregate welfare. However, political influence may also be strongly biased in favour of a single country. Under simple majority voting in the regulatory board, for example, the median voter holds dictatorial powers over centralized regulatory policy. If it so happens that the median voter

[16] The difference in virtual marginal maintenance cost between Integration and Common regulation equals $-(\lambda v^2 + 2\underline{\xi}^I)\Phi'(\widetilde{q})/2v(1-v)$ in the intermediate case and $(\lambda v^2 + 2\underline{\xi}^I)\Phi'(\underline{q})/2(1-v)^2$ in the low productivity case; compare (16) and (22).

belongs to a country with small gains from market integration, the problem of inferior maintenance spending under centralized regulation is so serious that productive inefficiencies become of second order for network reliability. Decentralizing power to a set of national regulatory agencies is then better than creating a common regulatory agency.

What kind of political process could possibly lead to the creation of a common regulatory agency (CRA) whose policies would be to the detriment of some countries? Obviously, if every country had veto power over centralized regulatory policies, any regulatory policy implemented by the CRA would necessarily constitute a Pareto improvement.[17] The CRA would be maximizing a weighted average of national welfare as before, but now subject to additional veto constraints, $W_i(\mathbf{Q}, \mathbf{u}_i) \geq W_i(\mathbf{Q}^S, \mathbf{u}_i^S)$, $i = 1, 2$. Welfare losses thus arise under centralized regulation only if (i) individual countries do not have veto power; or (ii) whoever controls the veto in the country pursues an objective different from national welfare maximization. In regards to the first issue, the European Union constitutes an example of multi-national political cooperation with limited veto rights. Participation in the EU is voluntary, but the member states delegate important policy decisions to EU authorities, energy policy being a prominent example.

I run the above analysis under the restriction of symmetric regulatory policies in the two countries. This restriction is not innocuous, although the CRA would in fact maximize aggregate welfare, even with full policy discretion, in the special case where political power is perfectly balanced ($\mu_1 = \mu_2 = 1/2$). To see the importance of policy symmetry, assume instead that the CRA has full policy discretion, one single country controls the CRA ($\mu_i = 1$), and that the gains from integration are symmetric ($S_1 = S_2 = S$). For any domestic regulatory policy $\mathbf{q}_i$, country i, controlling the centralized regulatory agency, would push maintenance spending abroad as high as possible (raise $\mathbf{q}_j$ up to the point at which $W_j(\mathbf{Q}, \mathbf{u}_j) = W_j(\mathbf{Q}^S, \mathbf{u}_j^S)$ with veto rights) because the perceived social costs of transfers abroad are zero. The regulatory policies under full discretion would be highly asymmetric in this case. Constraining policies to be proportional and non-discriminatory (i.e. symmetric) will discipline the regulator. Under policy symmetry, the perceived marginal benefit of network reliability equals

$$2P_i'(q)(\mu_1 S_1 + \mu_2 S_1) = 2P_i'(q)(\mu_1 + \mu_2)S = 2P_i'(q)S,$$

which is completely independent of the distribution of political power. Under symmetry (both in terms of policy and gains from trade), the CRA maximizes aggregate welfare even when political power is strongly biased ($\mu_i = 1$). Proportionality and non-discrimination forces the CRA to internalize parts of the social costs of transfers abroad. Under symmetric gains from integration, there is full internalization of all social costs.

[17] Bargaining over regulatory policies would maximize aggregate welfare even under decentralized regulation provided the NRAs had access to productivity dependent lump-sum transfers. Normally, regulators have very limited possibilities for side transfers. Side transfers among system operators (typically in the form of cross-border congestion rents) will not do as a substitute because they might interfere with incentive compatibility and participation constraints of the system operators.

Which is the optimal number of system operators? Whether centralizing network management in the hands of a common system operator (CSO) is better than maintaining national system operators (NSOs) depends on the characteristics of the network. Assume that network operation initially is split among two NSOs. The optimal regulatory policy from the viewpoint of the common regulatory agency (CRA) then equals $\mathbf{q}^{Cr}$ characterized in Lemma 3. However, the CRA could implement $\mathbf{q}^{Cr}$ even under the alternative structure where there is a single CSO. Expected network reliability and social maintenance costs would be the same under both structures. The choice between one or two system operators then boils down to minimizing operator rent. In a system with two NSOs, expected operator rent equals

$$2v^2\Phi(\widetilde{q}^{Cr}) + 2v(1-v)\Phi(\underline{q}^{Cr})$$

whereas the regulator expects to leave an operator rent of

$$v^2(\Phi(\underline{q}^{Cr}) + \max\{\Phi(\widetilde{q}^{Cr}); \Phi(\underline{q}^{Cr})\}) + 2v(1-v)\Phi(\underline{q}^{Cr})$$

whenever there is a single CSO. Subtracting the two expressions, we see that operator rent is smaller with a CSO than two NSOs if and only if $\underline{q}^{Cr} < \widetilde{q}^{Cr}$. This inequality always holds under network complementarity (see the proof of Lemma 3), and therefore it is cheaper for the CRA to implement $\mathbf{q}^{Cr}$ under a common system operator than with two national system operators.

Proposition 2 *Under network complementarity ($P''_{ij} > 0$ for all q) the common regulatory agency prefers a common system operator to two national system operators.*

The proof is in the Appendix.

To understand why it is better to merge system operation in this case, consider the case where both networks are of high productivity ($\beta_1 = \beta_2 = \overline{\beta}$). An understatement of productivity from $\overline{\beta}$ to $\underline{\beta}$ by NSO 2 affects transfers to both NSOs owing to the interdependence of network reliability. NSO 2 itself cannot gain by understating productivity (by incentive compatibility). By complementarity, the optimal quality of network 1 falls with perceived productivity of network 2. As a consequence, even the transfer payments to NSO 1 fall. Under complementarity, therefore, NSO 2 imposes a *negative informational rent externality* on NSO 1 by understating productivity (the magnitude of this externality equals $v^2[\Phi(\widetilde{q}^{Cr}) - \Phi(\underline{q}^{Cr})]$). By merging system operation, the regulator forces the system operators to internalize the negative rent externality by cross-subsidization and therefore manages to limit operator rent.

The presence of a negative informational rent externality renders it optimal from the single regulator's point of view to reduce the number of system operators. Conversely, the regulator optimally divides network responsibility among multiple system operators in case of a *positive informational rent externality.* A CSO would have an incentive to understate productivity to increase transfers resulting from exaggerated benefits of maintenance spending in other parts of the network. The regulator can mitigate the exercise of such *agency power* by splitting system operation between a set of national system operators.

Whereas network complementarity constitutes a sufficient condition for a negative rent externality, network substitutability is a necessary, but not sufficient condition for a positive rent externality. A cost complementarity between the different parts of the network operated by the CSO pulls in the opposite direction. Understating productivity, or equivalently exaggerating maintenance cost, in one part of the network shifts the virtual marginal maintenance cost upwards in the other part of the network.[18] This is due to the fact that agency power renders it particularly expensive in terms of informational rent to maintain a high quality of the lowest productivity network (i.e. $\beta = (\underline{\beta}, \underline{\beta})$). This cost complementarity dominates whenever the cost of informational rent (measured by λv) is high. In the opposite case, network substitutability dominates cost complementarity and positive rent externalities arise under the CSO.

Proposition 3 *Under network substitutability ($P''_{ij} < 0$ for all q) and if the social cost of informational rent (λv) is low, the common regulatory agency prefers to divide system operation between two national system operators instead of having a common system operator.*

The proof is in the Appendix.

As network characteristics are fundamentally related to network topology, we can draw some conclusions regarding optimal system operation in relation to network topology. In Section 2, I argued by means of a simple example that radial networks tend to display network complementarities. Thus, the responsibility for maintaining the radial networks should optimally be left in the hands of a single system operator. Conversely, the different parts of the meshed network tend to be substitutable. Under some circumstances (e.g. when the social cost of informational rent is low) the responsibility for the meshed network should optimally be split between multiple system operators.

The practical relevance of studying the shadow price becomes clear in the light of the wave of regulatory reform that has swept across Europe. As more and more countries replace rate-of-return regulation, whose main purpose is to limit operator rent, with more high-powered income regulation, whose main purpose is to increase cost efficiency, it would appear that the social cost of operator rent has fallen in Europe.[19]

Which is the optimal governance structure? In this final part I combine the partial results on regulation and system operation to draw conclusions about the optimal governance structure. Propositions 1, 2 and 3 can be summarized in the following table:

Centralized regulation welfare dominates decentralized regulation if the common regulatory agency (CRA) is equipped to balance the political influence of the participating countries (μ_i is

[18] Assuming that the productivity of network i is low, the virtual marginal maintenance cost of network i is $\Phi'(q)(\lambda v^2 + 2\underline{\xi}^I)/2v(1-v)^2$ higher if network j is of low productivity than if j is of high productivity.

[19] It could also be that the simultaneous development of the incentive theory of regulation served as an input for regulatory reform.

	μ_j high, S_j low	μ_i close to 1/2
$P_{ij} < 0$, λv low	*Separation/Common agency*	*Common regulation*
$P_{ij} > 0$	*Separation/Common agency*	*Integration*

Table 2: The optimal network governance structure

close to 1/2). With balanced political influence, the CRA acts nearly as the benevolent social planner. If the network displays complementarities ($P_{ij} > 0$), the CRA prefers to merge system operation, and therefore Integration is the socially optimal network structure. In case of network substitutability and if the social cost of transfers is low ($P_{ij} < 0$ and λv low), the CRA splits system operation across as set of national system operators, so Common regulation is the socially optimal network structure. In case political power is collected in the hands of a country with little to gain from market integration (μ_j high, $S_j$low) decentralized regulation is optimal from society's viewpoint. Whether system operation should be split or merged in this case is difficult to answer. However, the mode of system operation probably does not matter much. As one country (j) has weak incentives to maintain its part of the network, the network externalities are weak independently of whether there is one or multiple system operators. In this case, the regulatory policies would be nearly the same under Separation as Common agency.

5 Conclusion

No network governance structure does uniformly better and no governance structure performs uniformly worse than all others in this model. Rather, optimal governance depends on (*i*) *political factors*, i.e., how well the common regulatory agency is set up to balance the economic interests of the different countries; (*ii*) *technological factors*, i.e., network substitutability versus complementarity; (*iii*) *economic factors*, i.e., how the gains from energy market integration vary across countries, and the social cost of operator rent.

Having a common regulatory agency is better from a welfare perspective than maintaining national regulatory agencies on the proviso that political influence is sufficiently balanced across the countries participating in the common regulatory agency. With an equal distribution of political power, no country can exert enough influence over regulatory policy to tilt it in one's own favour. The importance of balanced political influence is well understood by the European Union. The Board of Regulators of the Agency for the Cooperation of Energy Regulators (ACER) resides under instructions to act independently from any government of a member state. Only one representative per member state may be admitted to the Board of Regulators, and the board members have one vote each (EU, 2009a).

With balanced political influence, the preferences of the regulator are aligned with those of the benevolent social planner. Under those conditions, a common system operator is socially optimal when there are negative rent externalities associated with under-performance, whereas splitting network operation is socially optimal if the rent externalities are positive. For an illustrative example of a positive rent externality, recall the capacity problems between Norway and Sweden described in the Introduction. In May 2008, precisely when the interconnections between southern Norway and southern Sweden failed, the NorNed cable connecting southern Norway and the Netherlands went operational. The longest submarine power cable in the world, NorNed was a prestige project for its owners Statnett and TenneT (the dutch system operator). Reduced export capacity from southern Norway to southern Sweden, combined with a large electricity surplus that year, pushed down prices in southern Norway and increased the value of electricity trade between the Netherlands and southern Norway. Being the only transmission line directly connecting the two markets, NorNed could sell its transmission capacity at a vastly higher price than projected (Statnett, 2008). Statnett probably internalized part of the increased profitability of the NorNed cable resulting from reduced capacity on its Norwegian-Swedish interconnection. The perceived value of repairing the Norwegian-Swedish connection might have been higher had NorNed instead been fully owned by TenneT, or had the interconnection broken down on the Swedish instead of the Norwegian side of the border. Whether the repairs would have been carried out more expediently under different ownership of the interconnections, remains a matter of speculation.

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Appendix

This appendix contains the proofs of all lemmas and propositions in the main text of "Optimal transmission regulation of an integrated energy market".

Proof of Lemma 1

By the boundary condition (2), all possible maxima of $W_1(\mathbf{Q},\mathbf{0})+W_2(\mathbf{Q},\mathbf{0})$ by necessity are contained in $[0,k]^8$. Maximization of a continuous function on a compact set yields an optimum. Concavity of P and strict convexity of ψ render aggregate welfare strictly concave, hence the solution is unique. The solution is interior by the assumption that $P_i'(0,q_j)>0$ for all $q_j\geq 0$ and $\psi'(0)=0$. Symmetry of P, λ and ψ render the solution symmetric. Thus, the first-order conditions (focs) given by (3) characterize the unique solution. Define $(q_1^{fb}(\beta),q_2^{fb}(\beta))$ as the implicit solution to $P_1'(q_1^{fb},q_2^{fb})(S_1+S_2)=(1+\lambda)\psi'(q_1^{fb}/\beta_1)/\beta_1$ and $P_2'(q_1^{fb},q_2^{fb})(S_1+S_2)=(1+\lambda)\psi'(q_2^{fb}/\beta_2)/\beta_2$. Straightforward differentiation yields:

$$\frac{dq_i^{fb}}{d\beta_j}=\frac{P_{ij}''(S_1+S_2)(1+\lambda)(q_j^{fb}\psi_{jj}''+\psi_j'/\beta_j)}{(P_{11}''P_{22}''-P_{12}''P_{21}'')(S_1+S_2)^2-(1+\lambda)(P_{11}''\psi_{22}''+P_{22}''\psi_{11}'')(S_1+S_2)+(1+\lambda)^2\psi_{11}''\psi_{22}''}$$

where $\psi_i'=\psi'(q_i^{fb}/\beta_i)/\beta_i$ and $\psi_{ii}''=\psi''(q_i^{fb}/\beta_i)/\beta_i^2$. By concavity of P and strict convexity of ψ, the denominator is positive, so $dq_i^{fb}/d\beta_j>0$ if $P_{ij}''>0$, but $dq_i^{fb}/d\beta_j<0$ if $P_{ij}''<0$. ■

Proof of Lemma 2

Assume that both NRAs have committed to dominant strategy implementable direct (DSID) contracts. Consider the Lagrangian

$$L_i^S(\mathbf{Q},\chi_i,\xi_i,\boldsymbol{\alpha}_i)=W_i^S(\mathbf{Q})+\chi_i(\overline{q}_i-\widetilde{q}_i)+\xi_i(\widehat{q}_i-\underline{q}_i)+\boldsymbol{\alpha}_i\mathbf{q}_i,$$

where $\chi_i\geq 0$ and $\xi_i\geq 0$ are the Kuhn-Tucker multipliers associated with $\overline{q}_i\geq\widetilde{q}_i$ and $\widehat{q}_i\geq\underline{q}_i$, and $\boldsymbol{\alpha}_i=(\overline{\alpha}_i,\widehat{\alpha}_i,\widetilde{\alpha}_i,\underline{\alpha}_i)\geq\mathbf{0}$ are the Kuhn-Tucker multipliers associated with non-negative quality, $\mathbf{q}_i\geq\mathbf{0}$. Concavity of P plus strict convexity of ψ and Φ render W_i^S strictly concave in $\mathbf{q}_i$. Strict concavity of W_i^S and linearity of the constraints render L_i^S strictly concave in $\mathbf{q}_i$. Thus, every solution $(\mathbf{q}_i^S,\chi_i^S,\xi_i^S)$, $\boldsymbol{\alpha}_i^S$, $i=1,2$, to the first-order conditions $\partial L_i^S/\partial\mathbf{q}_i=\mathbf{0}$ and associated complementary slackness conditions constitutes an equilibrium of this game.

Define $\Omega_i=(\mathbf{q}_i,\chi_i,\xi_i)$, $\Omega=(\Omega_1,\Omega_2)$, $l_i(\Omega)=(\boldsymbol{\alpha}_i-\partial L_i^S/\partial\mathbf{q}_i,\overline{q}_i-\widetilde{q}_i,\widehat{q}_i-\underline{q}_i)$ and $l(\Omega)=(l_1(\Omega),l_2(\Omega))$. By construction, every equilibrium $(\mathbf{q}_i^S,\chi_i^S,\xi_i^S)$, $\boldsymbol{\alpha}_i^S$, $i=1,2$, of the game is a solution to the complementary problem:

$$\text{Find } \Omega \geq 0 \text{ such that } l(\Omega) \geq 0,\ \Omega_i l_i(\Omega) = 0,\ i = 1, 2. \tag{A.1}$$

Conversely, every solution to (A.1) characterizes an equilibrium of the game with $\boldsymbol{\alpha}_i$ appropriately defined. Thus, there are exactly as many equilibria of the game as there are solutions to (A.1).

The mapping l is continuously differentiable by the assumption that P_i', ψ' and Φ' are continuously differentiable. Thus, (A.1) has a unique solution if (i) every solution to (A.1) is an element of a compact set; (ii) l satisfies an appropriate regularity condition; and (iii) the Jacobian of l, eliminating rows and columns with elements of zero, is positive at all solutions to (A.1); see Kolstad and Mathiesen (1987).

Condition (i): For all $\widetilde{q}_1 \geq k > 0$,

$$\begin{aligned} \widetilde{\alpha}_1 - \partial L_1^S/\partial \widetilde{q}_1 &= \chi_1 + v(1-v)[(1+\lambda)(\psi'(\widetilde{q}_1/\underline{\beta})/\underline{\beta} + \frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi'(\widetilde{q}_1)) - P_1'(\widetilde{q}_1, \widehat{q}_2)S_1] \\ &> v(1-v)((1+\lambda)\psi'(\widetilde{q}_1/\underline{\beta})/\underline{\beta} - P_1'(\widetilde{q}_1, \widehat{q}_2)(S_1+S_2)) > 0, \end{aligned}$$

where the second inequality follows from (2). By necessity, then, every solution to (A.1) satisfies $\widetilde{q}_1 \in [0, k)$. For all $\overline{q}_1 \geq k > \widetilde{q}_1$,

$$\overline{\alpha}_1 - \partial L_1^S/\partial \overline{q}_1 = v^2((1+\lambda)\psi'(\overline{q}_1/\overline{\beta})/\overline{\beta} - P_1'(\overline{q}_1, \overline{q}_2)S_1) - \chi_1$$

which is strictly positive by (2) and $\chi_1(\overline{q}_1 - \widetilde{q}_1) = 0$. Thus, every solution to (A.1) satisfies even $\overline{q}_1 < k$. Suppose $\overline{q}_1 = 0$. Then

$$\overline{\alpha}_1 - \partial L_1^S/\partial \overline{q}_1 = -v^2 P_1'(0, \overline{q}_2)S_1 - \chi_1 < 0$$

by the assumptions that $P_1'(0, q_2) > 0$ for all $q_2 \geq 0$ and $\psi'(0) = 0$. Thus, $\overline{q}_1 \in (0, k)$. In this case, $\widetilde{\alpha}_1 - \partial L_1^S/\partial \widetilde{q}_1 = -v(1-v)P_1'(0, \widehat{q}_2)S_1 < 0$ at $\widetilde{q}_1 = 0$. Thus, $\widetilde{q}_1 \in (0, k)$. By analogous arguments, $\underline{q}_1 \in (0, k)$ and $\widehat{q}_1 \in (0, k)$. Consider next the multiplier χ_1. Since $\overline{q}_1 > 0$, $\overline{\alpha}_1 - \partial L_1^S/\partial \overline{q}_1 = 0$ and therefore

$$\chi_1 = v^2[(1+\lambda)\psi'(\overline{q}_1/\overline{\beta})/\overline{\beta} - P_1'(\overline{q}_1, \overline{q}_2)S_1] \leq \max_{q \in [0,k]^2} v^2[(1+\lambda)\psi'(q_1/\overline{\beta})/\overline{\beta} - P_1'(q)S_1].$$

Thus, $\chi_1 \geq 0$ is bounded from above. Analogously, $\xi_1 \geq 0$ is bounded from above. Similarly, Ω_2

is contained in a compact and convex set. This concludes the proof that every possible solution to (A.1) is an element of a compact (and convex) set.

Condition (*ii*): The regularity condition states at every solution Ω to (A.1), $\Omega_i = 0$ implies $l_i(\Omega) > 0$. Regularity is a generic property and satisfied for almost all parameter values.

Condition (*iii*): It is easy to verify that the Jacobian of $l(\Omega)$ has strictly positive leading principal minors for all $\Omega \geq 0$ and therefore is positive definite.

The complementary problem (A.1) has a unique solution, and there exists a unique equilibrium of the game for generic parameter values. To verify that this solution is given by (10), it is sufficient to check that (10) satisfies $\mathbf{Q}^S > \mathbf{0}$, $\overline{q}_i^S > \widetilde{q}_i^S$ and $\widehat{q}_i^S > \underline{q}_i^S$. The assumptions $P_1'(0, q_2) > 0$ for all $q_2 \geq 0$, $P_2'(q_1, 0) > 0$ for all $q_1 \geq 0$ and $\psi'(0) = \Phi'(0) = 0$ render the solution interior ($\mathbf{Q}^S > 0$). I finally demonstrate that $\overline{q}_i^S > \widetilde{q}_i^S$ and $\widehat{q}_i^S > \underline{q}_i^S$. Define the generalized (strictly convex) virtual maintenance cost

$$\begin{aligned} c(q_i;\beta_i) = &\ (1+\lambda)[\tfrac{\beta_i-\underline{\beta}}{\overline{\beta}-\underline{\beta}}\psi(q_i/\overline{\beta}) + \tfrac{\overline{\beta}-\beta_i}{\overline{\beta}-\underline{\beta}}(\psi(q_i/\underline{\beta}) + \frac{v}{1-v}\frac{\lambda}{1+\lambda}\Phi(q_i))] \\ = &\ (1+\lambda)[\psi(q_i/\overline{\beta}) + \tfrac{\overline{\beta}-\beta_i}{\overline{\beta}-\underline{\beta}}(1+\frac{v}{1-v}\frac{\lambda}{1+\lambda})\Phi(q_i)], \end{aligned} \tag{A.2}$$

where I have used $\Phi(q_i) = \psi(q_i/\underline{\beta}) - \psi(q_i/\overline{\beta})$. Let $c_i'(q_i;\beta_i) = \partial c(q_i;\beta_i)/\partial q_i$ and $c_{ii}''(q_i;\beta_i) = \partial^2 c(q_i;\beta_i)/\partial q_i^2 > 0$. Define $q^S(\beta_i,\beta_j)$ as the implicit solution to $P_i'(q^S)S_i = c_i'(q_i^S;\beta_i)$, $i = 1,2$. Now, $\overline{q}_i^S - \widetilde{q}_i^S = \int_{\underline{\beta}}^{\overline{\beta}}[\partial q_i^S(\beta_i,\overline{\beta})/\partial\beta_i]d\beta_i > 0$ because

$$\frac{\partial q_i^S(\beta_i,\beta_j)}{\partial\beta_i} = \frac{(1+\lambda)(1+\frac{v}{1-v}\frac{\lambda}{1+\lambda})\Phi'(q_i^S)(\partial^2 c_{jj}'' - P_{jj}''S_j)/(\overline{\beta}-\underline{\beta})}{(P_{11}''P_{22}'' - P_{12}''P_{21}'')S_1S_2 - P_{11}''c_{22}''S_1 - P_{22}''c_{11}''S_2 + c_{11}''c_{22}''} > 0.$$

By implication even $\widehat{q}_i^S - \underline{q}_i^S = \int_{\underline{\beta}}^{\overline{\beta}}[\partial q_i^S(\beta_i,\underline{\beta})/\partial\beta_i]d\beta_i > 0$.

Having established existence and uniqueness, I now turn to the comparative statics of the equilibrium contracts. Consider first the problem of overall under-spending ($P(q^S) < P(q^{fb})$). The proof is in two steps. First, I consider under-spending as a failure to internalize trade externalities, ignoring the effects of informational rent. I then show that informational rent induces an additional distortion under Separation. Define $z^{fb}(\theta)$ as the implicit solution to $P_i'(z^{fb})(S_i + \theta S_j) = \psi'(z_i^{fb}/\beta_i)/\beta_i$, $i \neq j = 1,2$. By construction $z^{fb}(1) = q^{fb}$, and $z^{fb}(0)$ is the equilibrium under Separation when the NRAs do not take the social cost of informational rent into account. Differentiation yields:

$$\frac{dz_i^{fb}}{d\theta} = \frac{P_i'(\psi_{jj}'' - P_{jj}''(\theta S_i + S_j))S_j + P_j'P_{ij}''(S_i+\theta S_j)S_i}{(P_{ii}''(S_i+\theta S_j) - \psi_{ii}'')(P_{jj}''(\theta S_i + S_j) - \psi_{jj}'') - P_{ji}''(\theta S_i + S_j)P_{ij}''(S_i+\theta S_j)},$$

which is of ambiguous sign. Total differentiation of $P(z^{fb}(\theta))$, with simplification and using symmetry ($P''_{ji} = P''_{ij}$), yields:

$$\frac{dP}{d\theta} = \frac{\sum_{i\neq j=1,2}((P'_i)^2\psi''_{jj}S_j + P'_i(P'_jP''_{ij} - P'_iP''_{jj})(\theta S_i + S_j)S_j)}{(P''_{ii}(S_i+\theta S_j) - \psi''_{ii})(P''_{jj}(\theta S_i + S_j) - \psi''_{jj}) - P''_{ji}(\theta S_i + S_j)P''_{ij}(S_i+\theta S_j)},$$

which is positive under condition (4). Hence, $P(q^{fb}) > P(z^{fb}(0))$. Consider next the effect of informational rent. Differentiate q_i^S with respect to v:

$$\frac{dq_i^S}{dv} = \frac{-(c''_{jj} - P''_{jj}S_j)\partial c'_i/\partial v - P''_{ij}S_i\partial c'_j/\partial v}{(P''_{11}P''_{22} - P''_{12}P''_{21})S_1S_2 - (P''_{11}c''_{22}S_1 + P''_{22}c''_{11}S_2) + c''_{11}c''_{22}},$$

which can be positive or negative. Total differentiation of $P(q^S)$ with respect to v, with simplification and using symmetry ($P''_{ji} = P''_{ij}$), yields:

$$\frac{dP(q^S)}{dv} = \frac{-\sum_{i\neq j=1,2}(P'_ic''_{jj}\partial c'_i/\partial v + (P'_iP''_{ji} - P'_jP''_{ii})S_i\partial c'_j/\partial v)}{(P''_{11}P''_{22} - P''_{12}P''_{21})S_1S_2 - (P''_{11}c''_{22}S_1 + P''_{22}c''_{11}S_2) + c''_{11}c''_{22}}.$$

Under condition (4), $dP(q^S)/dv \leq 0$. Since $q_i^S|_{v=0} = z_i^{fb}(0)$, $P(q^S) \leq P(z^{fb}(0))$. Under condition (4), therefore, $P(q^S) \leq P(z^{fb}(0)) < P(q^{fb})$.

To see that NSO 1 overinvests relative to NSO 2 under Separation when $S_1 > S_2$, fix aggregate quality at $q_1^S(\beta) + q_2^S(\beta)$ and implicitly define $x_1(\kappa)$ by

$$\frac{P'_1(x_1, q_1^S(\beta) + q_2^S(\beta) - x_1)}{P'_2(x_1, q_1^S(\beta) + q_2^S(\beta) - x_1)}\kappa = \frac{c'_1(x_1;\beta_1)}{c'_2(q_1^S(\beta) + q_2^S(\beta) - x_1;\beta_2)},$$

where $\kappa \in [1, S_1/S_2]$. By construction, $x_1(S_1/S_2) = q_1^S(\beta)$. The second-best optimal distribution of quality given total quality $q_1^S(\beta)+q_2^S(\beta)$ equals $x_1(1)$ and $x_2(1) = q_1^S(\beta)+q_2^S(\beta)-x_1(1)$ because this is the point at which the marginal rate of substitution equals the (virtual) marginal technical rate of substitution. Differentiate and substitute in $\kappa = P'_2c'_1/c'_2P'_1$ to get

$$x'_1(\kappa) = \frac{(P'_1)^2(c'_2)^2}{\sum_{i\neq j=1,2}(P'_1P'_2c'_ic''_{jj} + (P'_iP'_{ji} - P'_jP''_{ii})c'_1c'_2)},$$

which is strictly positive under condition (4). Thus, $S_1 > S_2$ implies relative overinvestment in 1 ($q_1^S(\beta) = x_1(S_1/S_2) > x_1(1)$) and under-spending in 2 ($q_2^S(\beta) < q_1^S(\beta) + q_2^S(\beta) - x_1(1) = x_2(1)$) under Separation. ■

The relevance of dominant strategy implementable direct (DSID) mechanisms under Separation

The restriction to dominant strategy implementable direct (DSID) mechanisms is without loss of generality, in the sense that every quasi-dominant strategy equilibrium of a regulation game with general message space (defined below), can equivalently be represented as the equilibrium of a game where both regulators have committed to offering direct DSID mechanisms. The strategy of proof is similar to the one Attar et al. (2011) use to prove that the Revelation Principle holds when a single agent decides which of multiple principals to contract with.

Consider a regulatory game with a general message space. Assume that each national regulatory agency (NRA) $i = 1, 2$ has committed to a message space A_i, and a regulatory policy $(q_i^*, t_i^*) : A \to \mathbb{R}_+ \times \mathbb{R}$, where $A = (A_i, A_j)$ (by the assumption of full transparency, the message space and regulatory polices are common knowledge). Let $q^* = (q_i^*, q_j^*)$ and $t^* = (t_i^*, t_j^*)$. Moreover, $a_i^*(\beta_i) \in A_i$ is the message chosen by national system operator (NSO) i of type $\beta_i \in \{\underline{\beta}, \overline{\beta}\}$ under the regulatory policy (q^*, t^*), and $a^*(\beta) = (a_i^*(\beta_i), a_j^*(\beta_j))$. In a quasi-dominant strategy equilibrium of the regulation game with general message space A, (q^*, t^*) and $\{a^*(\beta)\}_{\beta \in \{\underline{\beta}, \overline{\beta}\}^2}$ satisfy for $i \neq j = 1, 2$ and for all $a_i, a_j \in A_i \times \{a_j^*(\underline{\beta}), a_j^*(\overline{\beta})\}$:

$$t_i^*(a_i^*(\beta_i), a_j) - \psi(q_i^*(a_i^*(\beta_i), a_j)/\beta_i) \geq t_i^*(a_i, a_j) - \psi(q_i^*(a_i, a_j)/\beta_i) \tag{A.3}$$

$$t_i^*(a^*(\beta)) - \psi(q_i^*(a^*(\beta))/\beta_i) \geq 0. \tag{A.4}$$

Condition (A.3) states that messages are required to be dominant strategies with respect to all messages reached by the opponent with *positive probability*, i.e. $a_j^*(\underline{\beta})$ and $a_j^*(\overline{\beta})$, but does not require dominance in regards to the entire message space A_j - hence, the label quasi-dominance. Condition (A.4) states that participation should be profitable in equilibrium. Stronger strategy requirements, like dominance regarding the entire message space A_j, could be placed on the regulatory policies. These added restrictions would (weakly) limit the set of equilibrium policies. A further equilibrium requirement is that there exists no (q_i, t_i) with corresponding messages $\{\widehat{a}(\beta)\}_{\beta \in \{\underline{\beta}, \overline{\beta}\}^2}$, where $\widehat{a}_i(\beta_i) \in A_i$ is the message chosen by i of type $\beta_i \in \{\underline{\beta}, \overline{\beta}\}$ under the regulatory policy (q_i, q_j^*, t_i, t_j^*), satisfying for $i \neq j = 1, 2$, and for all $a_i, a_j \in A_i \times \{\widehat{a}_j(\underline{\beta}), \widehat{a}_j(\overline{\beta})\}$:

$$t_i(\widehat{a}_i(\beta_i), a_j) - \psi(q_i(\widehat{a}_i(\beta_i), a_j)/\beta_i) \geq t_i(a_i, a_j) - \psi(q_i(a_i, a_j)/\beta_i), \tag{A.5}$$

$$t_i(\widehat{a}(\beta)) - \psi(q_i(\widehat{a}(\beta))/\beta_i) \geq 0, \tag{A.6}$$

$$
\begin{aligned}
\mathcal{W}_i(q_i, q_j^*, t_i) = & \; \textstyle\sum_{\beta \in \{\underline{\beta}, \overline{\beta}\}^2} \Pr(\beta)[P(q_i(\widehat{a}(\beta)), q_j^*(\widehat{a}(\beta))S_i - \psi(q_i(\widehat{a}(\beta))/\beta_i) - \lambda t_i(\widehat{a}(\beta))] \\
> & \; \textstyle\sum_{\beta \in \{\underline{\beta}, \overline{\beta}\}^2} \Pr(\beta)[P(q_i^*(a^*(\beta)), q_j^*(a^*(\beta))S_i - \psi(q_i(a^*(\beta))/\beta_i) - \lambda t_i(a^*(\beta))] \\
= & \; \mathcal{W}_i(q^*, t_i^*),
\end{aligned} \tag{A.7}
$$

where $\Pr(\overline{\beta}, \overline{\beta}) = v^2$, etc. Conditions (A.5)-(A.7) state that there should exist no strictly profitable quasi-dominant strategy implementable policy deviation (q_i, t_i) for i. Conditions (A.3)-(A.7) jointly define an equilibrium.

Consider instead an alternative game in which both regulators commit to offering DSID mechanisms. For $i = 1, 2$, let $q_i^S(\beta) = q_i^*(a^*(\beta))$ and $t_i^S(\beta) = t_i^*(a^*(\beta))$. It is easy to verify that (A.3) and (A.4) render truth-telling a (weakly) dominant strategy and participation profitable in the direct mechanism. To show that (q^S, t^S) does constitute an equilibrium, I need to verify that i cannot profitably deviate from (q_i^S, t_i^S) to some other DSID policy $(\widetilde{q}_i, \widetilde{t}_i)$ given (q_j^S, t_j^S). Suppose, on the contrary, that such a profitable deviation $(\widetilde{q}_i, \widetilde{t}_i)$ does exist. Return to the general message game, and define an alternative regulatory policy (q_i, t_i):

$$
(q_i(a), t_i(a)) = \begin{cases} (\widetilde{q}_i(\beta), \widetilde{t}_i(\beta)) & \text{if } a = a^*(\beta) \\ (h > 0, 0) & \text{for all } a \notin \{a_i^*(\underline{\beta}), a_i^*(\overline{\beta})\} \times A_j \end{cases}
$$

Under the assumption that j does not alter its message strategy with the introduction of the alternative strategy (q_i, t_i), i.e. $\widehat{a}_j(\underline{\beta}) = a_j^*(\underline{\beta})$ and $\widehat{a}_j(\overline{\beta}) = a_j^*(\overline{\beta})$, DSID of $(\widetilde{q}_i, \widetilde{t}_i)$ implies that an NSO i of type $\beta_i \in \{\underline{\beta}, \overline{\beta}\}$ earns a non-negative profit by reporting $\widehat{a}_i(\beta_i) = a_i^*(\beta_i)$ and cannot benefit from deviating to $a_i^*(b_i)$, where $b_i \in \{\underline{\beta}, \overline{\beta}\}$ and $b_i \neq \beta_i$. Deviating to $a_i \notin \{a_i^*(\underline{\beta}), a_i^*(\overline{\beta})\}$ is strictly unprofitable because then $t_i(a) - \psi(q_i(a)/\beta_i) = -\psi(h/\beta_i) < 0$. Given that j does not modify its message strategy under the new policy, it is not profitable for i to alter its message strategy, either. Since the regulatory policy (q_j^*, t_j^*) is the same as before, it is optimal for j to maintain its message strategy $\widehat{a}_j(\beta_j) = a_j^*(\beta_j)$ for all $\beta_j \in \{\underline{\beta}, \overline{\beta}\}$ given that i does not alter its message strategy under the new policy. Hence, unaltered message strategies are mutually optimal, and therefore (q_i, t_i) satisfies (A.5) and (A.6). Moreover

$$
\mathcal{W}_i(q_i, q_j^*, t_i) = \mathcal{W}_i(\widetilde{q}_i, q_j^S, \widetilde{t}_i) > \mathcal{W}_i(q^S, t_i^S) = \mathcal{W}_i(q^*, t_i^*),
$$

where the equalities hold by construction of the regulatory policies $(\widetilde{q}_i, \widetilde{t}_i)$ and (q^S, t^S), and the inequality follows from the assumption that a deviation to $(\widetilde{q}_i, \widetilde{t}_i)$ is strictly profitable. The existence of a profitable unilateral deviation contradicts the assumption that (q^*, t^*) is an equilibrium. Hence, if (q^*, t^*) is indeed an equilibrium, then there cannot exist any profitable unilateral DSID deviation $(\widetilde{q}_i, \widetilde{t}_i)$ from (q_i^S, t_i^S), and therefore (q^S, t^S) constitutes an equilibrium. The equilibrium policies and welfare are the same in both games, hence they are equivalent.

Proof of Lemma 3

Consider the unconstrained maximization of $\Gamma^{Cr}(\mathbf{q})$. I verify ex post that the (unique) solution satisfies $\mathbf{q}^{Cr} > \mathbf{0}$, $\overline{q}^{Cr} > \widetilde{q}^{Cr}$ and $\widehat{q}^{Cr} > \underline{q}^{Cr}$. By the boundary condition (2), all maxima of Γ^{Cr} by necessity are contained in $[0, k]^4$. Maximization of a continuous function on a compact set yields an optimum. Concavity of P, strict convexity of ψ and convexity of Φ render Γ^{Cr} strictly concave, hence the optimum is unique and given by $\mathbf{q}^{Cr}$, characterized in (16). The solution is interior ($\mathbf{q}^{Cr} > \mathbf{0}$) by the assumption that $P_1'(0, q_2) > 0$ for all $q_2 \geq 0$ and $\psi'(0) = \Phi'(0) = 0$. Now to the monotonicity constraints.

Quality complementarity implies $\overline{q}^{Cr} > \widehat{q}^{Cr} > \widetilde{q}^{Cr} > \underline{q}^{Cr}$: Recall the generalized virtual maintenance cost (A.2) and define implicitly $q^{Cr}(\beta)$ by $2P_i'(q^{Cr})(\mu_1 \triangle S_1 + \mu_2 \triangle S_2) = c_i'(q_i^{Cr}; \beta_i)$, $i = 1, 2$. Now, $\overline{q}^{Cr} - \widehat{q}^{Cr} = \int_{\underline{\beta}}^{\overline{\beta}} (\partial q_i^{Cr}(\overline{\beta}, \beta_j)/\partial \beta_j) d\beta_j$. Since

$$\frac{\partial q_i^{Cr}(\beta)}{\partial \beta_j} = \frac{2P_{ij}''(\mu_1 S_1 + \mu_2 S_2)(1+\lambda)(1 + \frac{v}{1-v}\frac{\lambda}{1+\lambda})\Phi'(q_j^{Cr})/(\overline{\beta} - \underline{\beta})}{4(P_{11}''P_{22}'' - P_{12}''P_{21}'')(\mu_1 S_1 + \mu_2 S_2)^2 - 2(P_{11}''c_{22}'' + P_{22}''c_{11}'')(\mu_1 S_1 + \mu_2 S_2) + c_{11}''c_{22}''},$$

$\overline{q}^{Cr} > \widehat{q}^{Cr}$ if $P_{ij}'' > 0$. Similarly, $\widetilde{q}^{Cr} - \underline{q}^{Cr} = \int_{\underline{\beta}}^{\overline{\beta}} (\partial q_i^{Cr}(\underline{\beta}, \beta_j)/\partial \beta_j) d\beta_j$ implies $\widetilde{q}^{Cr} > \underline{q}^{Cr}$ if $P_{ij}'' > 0$. I complete the quality complementarity case by showing that $\widehat{q}^{Cr} > \widetilde{q}^{Cr}$ if $P_{ij}'' > 0$. Suppose on the contrary that $P_{ij}'' > 0$ and $\widetilde{q}^{Cr} \geq \widehat{q}^{Cr} > 0$. Convexity of ψ and Φ then imply $P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr}) > P_1'(\widehat{q}^{Cr}, \widetilde{q}^{Cr})$; see (16). By $P_{11}'' < 0$, $\widetilde{q}^{Cr} \geq \widehat{q}^{Cr}$ implies $P_1'(\widehat{q}^{Cr}, \widetilde{q}^{Cr}) \geq P_1'(\widetilde{q}^{Cr}, \widetilde{q}^{Cr})$. Complementarity and $\widetilde{q}^{Cr} \geq \widehat{q}^{Cr}$ imply $P_1'(\widetilde{q}^{Cr}, \widetilde{q}^{Cr}) \geq P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr})$. Combining these inequalities I arrive at a contradiction: $P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr}) > P_1'(\widehat{q}^{Cr}, \widetilde{q}^{Cr}) \geq P_1'(\widetilde{q}^{Cr}, \widetilde{q}^{Cr}) \geq P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr})$. Thus, quality complementarity implies $\widehat{q}^{Cr} > \widetilde{q}^{Cr}$.

Quality substitutability implies $\widehat{q}^{Cr} > \overline{q}^{Cr} > \underline{q}^{Cr} > \widetilde{q}^{Cr}$: If $P_{ij}'' < 0$, then $\partial q_i^{Cr}(\beta)/\partial \beta_j < 0$ and therefore $\widehat{q}^{Cr} > \overline{q}^{Cr}$ and $\underline{q}^{Cr} > \widetilde{q}^{Cr}$, see above. Finally, $P_{ij}'' < 0$ implies $\overline{q}^{Cr} > \underline{q}^{Cr}$. Subtract the foc for $\overline{q}^{Cr}$ from the foc for $\underline{q}^{Cr}$ in (16) and rearrange:

$$\begin{aligned} & 2(P_1'(\underline{q}^{Cr}, \underline{q}^{Cr}) - P_1'(\overline{q}^{Cr}, \overline{q}^{Cr}))(\mu_1 S_1 + \mu_2 S_2) \\ = \; & (1+\lambda)[\psi'(\underline{q}^{Cr}/\overline{\beta})/\overline{\beta} - \psi'(\overline{q}^{Cr}/\overline{\beta})/\overline{\beta} + \left(1 + \tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\right)\Phi'(\underline{q}^{Cr})]. \end{aligned}$$

For $\underline{q}^{Cr} \geq \overline{q}^{Cr} > 0$, the right-hand side of the above expression is strictly positive because $\psi'' > 0$ and $\Phi' > 0$ for all $\underline{q}^{Cr} > 0$. Under quality substitutability, $\underline{q}^{Cr} \geq \overline{q}^{Cr}$ implies that the left-hand side is non-positive because $dP_1'(q_1,q_1) = (P_{11}''(q_1,q_1) + P_{12}''(q_1,q_1))dq_1 < 0$ - a contradiction. Thus, $P_{ij}'' < 0$ implies $\overline{q}^{Cr} > \underline{q}^{Cr}$.

The final part is to show the effect on network quality of increasing μ_i. By straightforward differentiation of $q^{Cr}(\beta)$:

$$\frac{dq_1^{Cr}}{d\mu_i} = \frac{2(P_1'c_{22}'' + 2(P_2'P_{12}'' - P_1'P_{22}'')(\mu_1 S_1 + \mu_2 S_2))(S_i - S_j)}{4(P_{11}''P_{22}'' - P_{12}''P_{21}'')(\mu_1 S_1 + \mu_2 S_2)^2 - 2(P_{11}''c_{22}'' + P_{22}''c_{11}'')(\mu_1 S_1 + \mu_2 S_2) + c_{11}''c_{22}''},$$

which is strictly positive if $S_i > S_j$ and condition (4) is satisfied. A similar expression holds for $dq_2^{Cr}/d\mu_i > 0$. ■

Proof of Lemma 4

Construct the Lagrangian

$$L^I(\mathbf{q},\overline{u}) = \Gamma^I(\mathbf{q},\overline{u}) + \widetilde{\xi}(2\overline{u} - \Phi(\underline{q}) - \Phi(\widetilde{q})) + 2\underline{\xi}(\overline{u} - \Phi(\underline{q})),$$

where $\widetilde{\xi}$ and $\underline{\xi}$ are the Kuhn-Tucker multipliers associated with $2\overline{u}^I \geq \Phi(\underline{q}) + \Phi(\widetilde{q})$ and $2\overline{u}^I \geq 2\Phi(\underline{q})$. Ignore for the moment the monotonicity constraint $\min\{\overline{q};\widehat{q}\} \geq \max\{\widetilde{q};\underline{q}\}$ and the non-negativity constraint $\mathbf{q} \geq 0$. Concavity of $\Gamma^I(\mathbf{q},\overline{u})$ and of both constraints imply concavity of $L^I(\mathbf{q},\overline{u})$. Hence, the first-order conditions and complementary slackness conditions characterized in (22) are necessary and sufficient for optimality of $L^I(\mathbf{q},\overline{u})$. By the boundary condition (2), every solution to the problem of maximizing $\Gamma^I(\mathbf{q},(\Phi(\underline{q}) + \max\{\Phi(\widetilde{q});\Phi(\underline{q})\})/2)$ is contained in $[0,k]^4$. Maximization of a continuous function over a compact (and convex) domain yields an optimum. The solution is interior ($\mathbf{q}^I > 0$) by the assumptions that $P_1'(0,q_2) > 0$ for all $q_2 \geq 0$ and $\psi'(0) = \Phi'(0) = 0$. To complete the existence proof, I verify the monotonicity constraint $\min\{\overline{q}^I;\widehat{q}^I\} \geq \max\{\widetilde{q}^I;\underline{q}^I\}$.

Quality complementarity implies $\overline{q}^I > \widehat{q}^I > \widetilde{q}^I > \underline{q}^I$: The proofs that $\overline{q}^I > \widehat{q}^I > \widetilde{q}^I$ under quality complementarity are analogous the proofs in Lemma 3 that complementarity implies $\overline{q}^{Cr} > \widehat{q}^{Cr} > \widetilde{q}^{Cr}$ and are thus omitted. To demonstrate $\widetilde{q}^I > \underline{q}^I$, it is sufficient to verify consistency. If $\widetilde{q}^I > \underline{q}^I$, then $2\overline{u}^I \geq \Phi(\underline{q}^I) + \Phi(\widetilde{q}^I) > 2\Phi(\underline{q}^I)$ and so $\underline{\xi}^I = 0$. Since $\widetilde{\xi}^I + \underline{\xi}^I = \lambda v^2/2$, $\widetilde{\xi}^I = \lambda v^2/2$. Define $z^I(\theta)$ by

$$2P_1'(z^I)(\mu_1 S_1 + \mu_2 S_2) = (1+\lambda)\psi'(z_1^I/\underline{\beta})/\underline{\beta} + \tfrac{\lambda v}{2(1-v)}(1 + \tfrac{1-\theta}{1-v})\Phi'(z_1^I)$$

$$2P_2'(z^I)(\mu_1 S_1 + \mu_2 S_2) = (1+\lambda)\psi'(z_2^I/\overline{\beta})/\overline{\beta} + (1-\theta)\left(1 + \lambda + \tfrac{\lambda v}{2(1-v)}(1 + \tfrac{1-\theta}{1-v})\right)\Phi'(z_2^I).$$

Plugging $\underline{\xi}^I = 0$ and $\widetilde{\xi}^I = \lambda v^2/2$ into (22), it is easy to confirm that $z_1^I(1) = \widetilde{q}^I$, $z_2^I(1) = \widehat{q}^I$ and $z_1^I(0) = z_2^I(0) = \underline{q}^I$. Straightforward differentiation of $z^I(\theta)$ yields $dz_1^I/d\theta > 0$ and $dz_2^I/d\theta > 0$ if $P''_{12} > 0$. So for $P''_{12} > 0$, $\widetilde{q}^I > \underline{q}^I$ is indeed consistent.

Quality substitutability implies $\widehat{q}^I > \overline{q}^I > \max\{\widetilde{q}^I, \underline{q}^I\}$: The proofs that $\widehat{q}^I > \overline{q}^I$ and $\overline{q}^I > \underline{q}^I$ under quality substitutability are analogous to the proofs in Lemma 3 that $P''_{ij} < 0$ implies $\widehat{q}^{Cr} > \overline{q}^{Cr}$ and $\overline{q}^{Cr} > \underline{q}^{Cr}$ and are thus omitted. The proof that $\overline{q}^I > \widetilde{q}^I$ under quality substitutability is analogous the proof in Lemma 2 that $\overline{q}_i^S > \widetilde{q}_i^S$ and is also omitted.

Consider next the effect of increasing μ_i whenever $S_i > S_j$. Generically, only one of the two constraints $2\overline{u}^I \geq \Phi(\underline{q}^I) - \Phi(\widetilde{q}^I)$ and $2\overline{u}^I \geq 2\Phi(\underline{q}^I))$ is binding with equality. Under comparative statics, we can therefore treat $\widetilde{\xi}^I$ and $\underline{\xi}^I$ as constants because either $\underline{q}^I > \widetilde{q}^I$, in which case $\widetilde{\xi}^I = 0$ and $\underline{\xi}^I = \lambda v^2/2$ or $\underline{q}^I < \widetilde{q}^I$, in which case $\underline{\xi}^I = 0$ and $\widetilde{\xi}^I = \lambda v^2/2$. Straightforward differentiation of the first-order conditions (22) yield $\partial\overline{q}^I/\partial\mu_i > 0$ and $\partial\underline{q}^I/\partial\mu_i > 0$, whereas $\partial\widehat{q}^I/\partial\mu_i > 0$ and $\partial\widetilde{q}^I/\partial\mu_i > 0$ are satisfied under the additional assumption that condition (4) is met.

The final part is to compare quality levels under Integration with quality levels under Common regulation. Moving from Common regulation to Integration is qualitatively the same as lowering the virtual marginal maintenance cost of the least productive network when the two networks differ in productivity. The difference is $(\lambda v^2 + 2\underline{\xi}^I)\Phi'(\widetilde{q})/2v(1-v) > 0$. Under quality complementarity, lower marginal cost in one part of the network translates into higher maintenance spending in the entire network. Thus, $\widehat{q}^I > \widehat{q}^{Cr}$ and $\widetilde{q}^I > \widetilde{q}^{Cr}$ in this case. A switch from Common regulation to Integration is qualitatively the same as raising the virtual marginal cost of both networks by the same factor when the two networks have the same low productivity. The difference is $(\lambda v^2 + 2\underline{\xi}^I)\Phi'(\underline{q})/2(1-v)^2 > 0$. Under quality complementarity, higher marginal costs in both parts of the network translate into lower maintenance spending in the entire network. Thus, $\underline{q}^I < \underline{q}^{Cr}$ in this case.

Under quality substitutability, $P'_1(q_1, q_1)$ is strictly decreasing in q_1. Thus, $\underline{q}^I \geq \underline{q}^{Cr}$ would imply $P'_1(\underline{q}^I, \underline{q}^I) \leq P'_1(\underline{q}^{Cr}, \underline{q}^{Cr})$. Convexity and the difference in virtual marginal maintenance would yield $P'_1(\underline{q}^I, \underline{q}^I) > P'_1(\underline{q}^{Cr}, \underline{q}^{Cr})$ for $\underline{q}^I \geq \underline{q}^{Cr}$, see the first-order conditions. This is a contradiction. Thus, $\underline{q}^I < \underline{q}^{Cr}$ even under quality substitutability. The case when the two networks differ in productivity is more complicated. Again, $\widetilde{q}^I > \widetilde{q}^{Cr}$ owing to a lower marginal cost under Integration. However, $\widehat{q}^I < \widehat{q}^{Cr}$ due to quality substitutability. The overall effect on network reliability is ambiguous, but under condition (4), the direct effect dominates and so $P(\widehat{q}^I, \widetilde{q}^I) > P(\widehat{q}^{Cr}, \widetilde{q}^{Cr})$; see the proof on Lemma 10 for an example of this type of result. ■

Proof of Proposition 1

I first demonstrate that Common regulation welfare dominates Separation (the case with two system operators) if and only if political power is sufficiently balanced. The proof that Integration welfare dominates Common agency (the case with a single system operator) under the same circumstances is analogous and thus omitted.

Let $\mathbf{q}^{Cr}(\mu_i)$ be the equilibrium policy function under Common regulation as a function of political power μ_i, where $\triangle S_i > \triangle S_j$. Define aggregate welfare under regulatory policy $\mathbf{q}^{Cr}(\mu_i)$:

$$w^{Cr}(\mu_i) = W_1(\mathbf{q}^{Cr}(\mu_i), \mathbf{q}^{Cr}(\mu_i), \mathbf{u}^{Cr}(\mu_i)) + W_2(\mathbf{q}^{Cr}(\mu_i), \mathbf{q}^{Cr}(\mu_i), \mathbf{u}^{Cr}(\mu_i)).$$

Differentiate:

$$\begin{aligned}\tfrac{dw^{Cr}}{d\mu_i} &= 2v^2[P_1'(\overline{q}^{Cr}, \overline{q}^{Cr})(S_1 + S_2) - (1+\lambda)\psi'(\overline{q}^{Cr}/\overline{\beta})/\overline{\beta}]\tfrac{d\overline{q}^{Cr}}{d\mu_i} \\ &+2v(1-v)[P_1'(\widehat{q}^{Cr}, \widetilde{q}^{Cr})(S_1 + S_2) - (1+\lambda)\psi'(\widehat{q}^{Cr}/\overline{\beta})/\overline{\beta}]\tfrac{d\widehat{q}^{Cr}}{d\mu_i} \\ &+2v(1-v)[P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr})(S_1 + S_2) - (1+\lambda)(\psi'(\widetilde{q}^{Cr}/\underline{\beta})/\underline{\beta} + \tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi'(\widetilde{q}^{Cr}))]\tfrac{d\widetilde{q}^{Cr}}{d\mu_i} \\ &+2(1-v)^2[P_1'(\underline{q}^{Cr}, \underline{q}^{Cr})(S_1 + S_2) - (1+\lambda)(\psi'(\underline{q}^{Cr}/\underline{\beta})/\underline{\beta} + \tfrac{v}{1-v}\tfrac{\lambda}{1+\lambda}\Phi'(\underline{q}^{Cr}))]\tfrac{d\underline{q}^{Cr}}{d\mu_i},\end{aligned}$$

substitute in (16) and simplify:

$$\begin{aligned}\tfrac{dw^{Cr}}{d\mu_i} &= 2(1-2\mu_i)(S_i - S_j)\{v^2 P_1'(\overline{q}^{Cr}, \overline{q}^{Cr})\tfrac{d\overline{q}^{Cr}}{d\mu_i} + (1-v)^2 P_1'(\underline{q}^{Cr}, \underline{q}^{Cr})\tfrac{d\underline{q}^{Cr}}{d\mu_i} \\ &+2v(1-v)[P_1'(\widehat{q}^{Cr}, \widetilde{q}^{Cr})\tfrac{d\widehat{q}^{Cr}}{d\mu_i} + P_1'(\widetilde{q}^{Cr}, \widehat{q}^{Cr})\tfrac{d\widetilde{q}^{Cr}}{d\mu_i}]\}.\end{aligned}$$

If condition (4) holds, then $d\mathbf{q}^{Cr}/d\mu_i > \mathbf{0}$ (Lemma 3), and $w^{Cr}(\mu_i)$ is single-peaked in μ_i with a unique optimum at $\mu_i = 1/2$. The policy function $\frac{1}{2}W_1(\mathbf{Q}, \mathbf{u}_1) + \frac{1}{2}W_2(\mathbf{Q}, \mathbf{u}_2)$ is a positive affine transformation of the aggregate welfare function $W_1(\mathbf{Q}, \mathbf{u}_1) + W_2(\mathbf{Q}, \mathbf{u}_2)$, and therefore $\mathbf{q}^{Cr}(1/2)$ characterizes the (unique) welfare optimum in the case of two system operators. By uniqueness and $\mathbf{q}^{Cr}(1/2) \neq \mathbf{q}^S$: $w^{Cr}(1/2) > W_1(\mathbf{q}_1^S, \mathbf{q}_2^S, \mathbf{u}_1^S) + W_2(\mathbf{q}_1^S, \mathbf{q}_2^S, \mathbf{u}_2^S)$. Thus, there exist $\underline{\mu}^{Cr} \in [0, 1/2)$ and $\overline{\mu}^{Cr} \in (1/2, 1]$ such that Common regulation welfare dominates Separation if and only if $\mu_i \in [\underline{\mu}^{Cr}, \overline{\mu}^{Cr}]$ - with strict welfare dominance in the interior.

To show that there are also circumstances under which it is strictly better from a welfare point of view to maintain a system with two national regulatory agencies than to establish a common regulatory agency, it is sufficient to show that Separation strictly welfare dominates both Common regulation and Integration under certain circumstances. For $\mu_1 = 0$, $\mathbf{q}^{Cr} \to \mathbf{0}$ and $\mathbf{q}^I \to \mathbf{0}$ as $S_2 \to 0$ because the perceived gains from market integration from the point of view of country 2 then vanish. Thus, $w^{Cr}(0) \to P(0,0)S_1$ and $w^I(0) \to P(0,0)S_1$ as $S_2 \to 0$. Under Separation, $\mathbf{q}_2^S \to \mathbf{0}$ as $S_2 \to 0$, but $\mathbf{q}_1^S \to \mathbf{y}^S = (\overline{y}^S, \overline{y}^S, \underline{y}^S, \underline{y}^S) > \mathbf{0}$, where $P_1'(\overline{y}^S, 0)S_1 =$

$c_1'(\overline{y}^S;\overline{\beta})$ and $P_1'(\underline{y}^S,0)S_1 = c_1'(\underline{y}^S;\underline{\beta})$. The policy $\mathbf{y}^S$ is also the welfare maximizing choice of $\mathbf{q}_1$ conditional on $S_2 = 0$ and $\mathbf{q}_2 = 0$. Thus, $\sum_{i=1,2} W_i(\mathbf{q}_1^S, \mathbf{q}_2^S, \mathbf{u}_i^S) > P(0,0)S_1$ if $\mu_1 = 0$ and $S_2 = 0$. By continuity, Separation strictly welfare dominates Common regulation and Integration for $\mu_2 \gtrsim 0$ and $S_2 \gtrsim 0$. ■

Proof of Proposition 2

Quality complementarity implies $\overline{q}^{Cr} > \widehat{q}^{Cr} > \widetilde{q}^{Cr} > \underline{q}^{Cr}$, see the proof of Lemma 3. The monotonicity constraint $\min\{\overline{q}^{Cr}, \widehat{q}^{Cr}\} \geq \max\{\widetilde{q}^{Cr}; \underline{q}^{Cr}\}$ is satisfied and so the CRA can implement $\mathbf{q}^{Cr}$ under a CSO by means of the transfers $2\overline{t} = 2\psi(\overline{q}^{Cr}/\overline{\beta}) + \Phi(\underline{q}^{Cr}) + \Phi(\widetilde{q}^{Cr})$, $\widehat{t} + \widetilde{t} = \psi(\widehat{q}^{Cr}/\overline{\beta}) + \psi(\widetilde{q}^{Cr}/\underline{\beta}) + \Phi(\underline{q}^{Cr})$ and $2\underline{t} = 2\psi(\underline{q}^{Cr}/\underline{\beta})$. I omit the proof, which simply amounts to verifying that the CSO's incentive and participation constraints are all met by this contract. Weighted welfare equals

$$\begin{aligned}
\Gamma^I(\mathbf{q}^I, \overline{u}^I) &> \Gamma^I(\mathbf{q}^{Cr}, (\Phi(\underline{q}^{Cr}) + \Phi(\widetilde{q}^{Cr}))/2) \\
&= \Gamma^{Cr}(\mathbf{q}^{Cr}) + \lambda v^2(\Phi(\widetilde{q}^{Cr}) - \Phi(\underline{q}^{Cr}))/2 \\
&> \Gamma^{Cr}(\mathbf{q}^{Cr}).
\end{aligned}$$

The first inequality follows from uniqueness of $\mathbf{q}^I \neq \mathbf{q}^{Cr}$ under Integration. The second inequality follows from $\widetilde{q}^{Cr} > \underline{q}^{Cr}$ under quality complementarity and $\Phi' > 0$. ■

Proof of Proposition 3

Quality substitutability implies $\widehat{q}^I > \overline{q}^I > \max\{\widetilde{q}^I, \underline{q}^I\}$, see the proof of Lemma 4. Both monotonicity constraints $\overline{q}^I \geq \widetilde{q}^I$ and $\widehat{q}^I \geq \underline{q}^I$ are met, so the CRA can implement $\mathbf{q}^I$ in dominating strategies under Common regulation by means of the transfers $\overline{t} = \psi(\overline{q}^I/\overline{\beta}) + \Phi(\widetilde{q}^I)$, $\widehat{t} = \psi(\widehat{q}^I/\overline{\beta}) + \Phi(\underline{q}^I)$, $\widetilde{t} = \psi(\widetilde{q}^I/\underline{\beta})$ and $\underline{t} = \psi(\underline{q}^I/\underline{\beta})$. Weighted welfare equals

$$\begin{aligned}
\Gamma^{Cr}(\mathbf{q}^{Cr}) &> \Gamma^{Cr}(\mathbf{q}^I) \\
&= \Gamma^I(\mathbf{q}^I, \overline{u}^I) + \lambda v^2(\Phi(\underline{q}^I) + \max\{\Phi(\widetilde{q}^I); \Phi(\underline{q}^I)\} - 2\Phi(\widetilde{q}^I))/2 \\
&\gtreqless \Gamma^I(\mathbf{q}^I, \overline{u}^I).
\end{aligned}$$

The first inequality follows from uniqueness of $\mathbf{q}^{Cr} \neq \mathbf{q}^I$ under Common regulation. The last inequality is non-negative if $\underline{q}^I \geq \widetilde{q}^I$, in which case Common regulation is strictly better than Integration. It is negative if $\underline{q}^I < \widetilde{q}^I$, and the welfare difference between Integration and Common regulation then is ambiguous. I now show how the sign of $\underline{q}^I - \widetilde{q}^I$ depends on the social cost λv of informational rent.

If the social cost λv of informational rent is low, then $\underline{q}^I \geq \widetilde{q}^I$. To prove this claim I only have to verify that $\underline{q}^I > \widetilde{q}^I$ is indeed consistent for low λv because the first-order conditions are necessary and sufficient. If $\underline{q}^I > \widetilde{q}^I$, then $2\overline{u}^I \geq 2\Phi(\underline{q}^I) > \Phi(\underline{q}^I) + \Phi(\widetilde{q}^I)$ and by implication $\widetilde{\xi}^I = 0$ and $\underline{\xi}^I = \lambda v^2/2$. Plugging these Kuhn-Tucker multipliers into (22), yields

$$\begin{aligned}
2P_1'(\overline{q}^I, \overline{q}^I)(\mu_1 S_1 + \mu_2 S_2) = & \quad (1+\lambda)\psi'(\overline{q}^I/\overline{\beta})/\overline{\beta} \\
2P_1'(\widehat{q}^I, \widetilde{q}^I)(\mu_1 S_1 + \mu_2 S_2) = & \quad (1+\lambda)\psi'(\widehat{q}^I/\overline{\beta})/\overline{\beta} \\
2P_1'(\widetilde{q}^I, \widehat{q}^I)(\mu_1 S_1 + \mu_2 S_2) = & \quad (1+\lambda)\psi'(\widetilde{q}^I/\underline{\beta})/\underline{\beta} \\
2P_1'(\underline{q}^I, \underline{q}^I)(\mu_1 S_1 + \mu_2 S_2) = & \quad (1+\lambda)(\psi'(\underline{q}^I/\underline{\beta})/\underline{\beta} + \tfrac{\lambda}{1+\lambda}\tfrac{v}{(1-v)^2}\Phi'(\underline{q}^I)).
\end{aligned}$$

For $\lambda v = 0$, it is easy to verify that $\underline{q}^I > \widetilde{q}^I$ by applying the same technique used to prove $\underline{q}^{fb} > \widetilde{q}^{fb}$ under substitutability in the proof of Lemma 1. By continuity, $\underline{q}^I > \widetilde{q}^I$ extends even to $\lambda v > 0$ if λv is not too large.

Next, I show that $\underline{q}^I < \widetilde{q}^I$ for λ large. For $\underline{q}^I \geq \widetilde{q}^I$ and for all $\lambda \geq 0$, the following chain of inequalities holds

$$\frac{P_1'(\widetilde{q}^I, \widehat{q}^I)}{P_1'(\underline{q}^I, \underline{q}^I)} = \frac{\psi'(\widetilde{q}^I/\underline{\beta})/\underline{\beta}}{\psi'(\underline{q}^I/\underline{\beta})/\underline{\beta} + \frac{\lambda}{1+\lambda}\frac{v}{(1-v)^2}\Phi'(\underline{q}^I)} \leq \frac{1}{1 + \frac{\lambda}{1+\lambda}\frac{v}{(1-v)^2}(1 - \frac{\underline{\beta}}{\overline{\beta}}\frac{\psi'(\widehat{q}^I/\overline{\beta})}{\psi'(\widetilde{q}^I/\underline{\beta})})} < 1,$$

The equality follows from rewriting the focs above, the first (weak) inequality follows from monotonicity of Φ' and the assumption that $\underline{q}^I \geq \widetilde{q}^I$ and the second (strict) inequality follows from $\psi'(\widetilde{q}^I/\overline{\beta})/\overline{\beta} < \psi'(\widetilde{q}^I/\underline{\beta})/\underline{\beta}$. If $\lambda \to \infty$, then $\widetilde{q}^I \to 0$, $\widehat{q}^I \to 0$ and $\underline{q}^I \to 0$ and therefore $P_1'(\widetilde{q}^I, \widehat{q}^I)/P_1'(\underline{q}^I, \underline{q}^I) \to 1$ (recall the assumption that $P_1'(q)$ is bounded for all $q \geq 0$), which is a contradiction. Thus, $\underline{q}^I < \widetilde{q}^I$ for all sufficiently large λ.

I finally show that $\underline{q}^I < \widetilde{q}^I$ for all v sufficiently close to 1. By assumption (2), $(\widetilde{q}^I, \widehat{q}^I) \in [0,k]^2$, $\underline{q}^I \in [0,k]$ for some $k > 0$ independent of v. By network substitutability, $P_1'(\widetilde{q}^I, \widehat{q}^I)/P_1'(\underline{q}^I, \underline{q}^I) \geq P_1'(k,k)/P_1'(0,0) > 0$. From the inequalities above, $\underline{q}^I \geq \widetilde{q}^I$ would imply $P_1'(\widetilde{q}^I, \widehat{q}^I)/P_1'(\underline{q}^I, \underline{q}^I) \to 0$ as $v \to 1$, which is a contradiction. Thus, $\underline{q}^I < \widetilde{q}^I$ for all v sufficiently close to 1. ■