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Abstract

Worldwide, but in particular in North America and Europe, the grid infrastructure managers are facing demands for reinvestments in new assets with higher on-grid and off-grid functionality in order to promote energy efficiency and low-carbon conversion of the energy sector. To meet societal policy objectives in terms of carbon dioxide emissions, both the composition of the generators in favor of distributed energy resources (DER) and the load, promoting integration with downstream energy useage, will change. In this paper, we chararcterize some of the effects of new asset investments policy on the network tasks, assets and costs and contrast this with the assumptions implicit or explicit in current economic network regulation. The resulting challenge is identified as the change in the direction of higher asymmetry of information and higher capital intensity, combined with ambiguities in terms of task separation. To provide guidance, we present a model of investment provision under regulation between a distribution system operator (DSO) and a potential investor-generation. The results from the model confirm the hypothesis that network regulation should find a focal point, should integrate externalities in the performance assessment and should avoid wide delegation of contracting-billing for smart-grid investments.

Keywords: regulation, energy, networks, investments

JEL Classification: D72, L51

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1 Introduction

Climate change policy in the post-Kyoto world has deep repercussions on the way we extract, produce, transport and consume natural resources in everyday life. Achieving a common aggregate goal by efforts in multiple countries, sectors and over generations is itself a daunting task for the world's governments, doing under uncertainty about the optimal path to achieve the target or even consensus about the strategic arbitrage between intertemporal welfare and final environmental state is even worse. In this paper, we highlight a necessary but not sufficient condition for the deployment of an effective climate change policy in practice: the coordination of energy network regulation.

By focusing at the regulation of the network, rather than the energy or services performed on the infrastructure, we intentionally abstract from highly relevant but methodologically different questions related to the demand and supply for energy, market efficiency and power. Further, the limitation to energy infrastructure regulation rather than the more general utility regulation also excludes interesting and challenging problems occurring in countries and jurisdictions with vertically integrated utilities, under electrification or with state-owned incumbents in generation. Finally, we primarily base the discussion on the most mature and widespread energy infrastructure: electricity grids, with some attention also given to gas network regulation. However, with an eye on particularly the European political and regulatory situation, we hope to show that [energy] network regulation as it is practiced currently is not adequate to support a climate change policy, neither in terms on dominant theoretical support, nor in terms of regulatory practice. Although our concern is based on primarily theoretical arguments, we believe that the findings are of applied relevance as well.

The outline is as follows: First we briefly resume the theoretical underpinnings of recent past and current network regulation paradigms, reviewing also their links to the standard "packages" frequently used in regulatory practice. Second, we contrast the "old world" assumptions for regulation with the particular technical and economical challenges brought by a likely implementation of climate change policy onto the electricity sector. Third,

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we review the effectiveness of the models previously cited in the case of climate change, drawing conclusions about some areas of concern. Fourth, we propose two theoretical streams of analysis that have not received sufficient attention, but that may be informative to the designers of the "new world" network regulation. Finally, we close the paper with some remarks about the feasibility of the changes and the seriousness of the problems identified.

1.1 Network operations in the climate change setting

There is some consensus as to the list of effects on network operations in a low-carbon future, although the quantitative estimation of their importance still needs more precision.

Pepermans et al. (2005) list as driving forces for DG introduction flexible and diversified energy services, such as (i) standby or peak use capacity (peak shaving), (ii) reliability and power quality, (iii) substitute for investments in grid expansion, (iv) ancillary services, and environmental concerns, i.e. (v) cogeneration CHP, and (vi) efficient use of inexpensive[1] energy resources. The policy issues are summarized as (i) high financial cost, (ii) limited choices of primary fuels, (iii) lower economic efficiency (primarily allocative efficiency), (iv) inefficient fuel utilization from an environmental viewpoint, (v) lower supply security, (vi) mixed power quality (system frequency, voltage level, change in power flow, reduced effectiveness of protection equipment, reactive power, power conditioning).

The reduction of carbon emissions is result of three complementary actions on the supply side: changes in fuel mix, shifts in generation technology and carbon capture and storage (CCS). We leave the latter part until the last section, thus addressing the decarbonization of the electricity sector through fuel and technology mix. The fuel choices are to be guided through an appropriate implementation of pricing mechanisms for the externalities related to CO2-emissions, such as ETS or equivalent, which lie beyond the scope of network regulation. The electricity generation park is planned to be extended substantially with renewable energy resources (RES), primarily wind, tidal power, biomass and photovoltaic (PV) generation, cf. EC (2007, 2009). The greatest absolute and relative increase among RES is found for windpower from 82 TWh produced in 2006 to 545 TWh planned[2] in 2020 EC(2007). The new RES will be smaller units than the current centralized plants as a consequence of exhausted locations, local NIMBY resistance, di-

[1] Note that the energy sources often are free (solar energy, tidal, wind) or even negatively priced (waste, industrial heat).

[2] Green-X model, least cost scenario in EC(2007).

minishing returns in resource availability and lower economies of scale for certain technologies. In particular for wind and solar, the lion's part of the increase will be made as distributed generation (DG), i.e. installations below 100 MW connected directly to the distribution network. For photovoltaic in Europe with the exception of Spain and Portugal, the installations are residential micro-generators connected directly to the low-voltage grid and used mainly for autoconsumption.

The load in the low-carbon power system is partially controlled by demand-side management (DSM) mechanisms that control interruptible loads, schedule consumption and charge local energy storages (vehicles, heat storage) with respect to local DG availability, real-time price signals from the retailers/DSO and local demand signals. In combination with energy efficiency applied to both residential, commercial and industrial load, the overall energy volume transported per customer is expected to decrease. However, with continued expansion of total power for household and commercial appliances, the peak load is likely not decreasing, or at least less than the total energy consumption.

In combination with the high increase in intermittent DER generation needing backup through generation or grid interconnection, the increased share of non-coincidental peak generation and the introduction of wide demand-side participation also in generation and power services, the network investment need is substantial,

The new RES Directive (EC 2009/29) explicitly stipulates (art 16:3 and 5) that electricity TSO and DSO are obliged to disclose cost and benefit analyses with respect to the connection of RES and that the residual costs are either shared among grid users (art 6) with respect to a objective, transparent and nondiscriminatory criteria (without stating those), or absorbed by the network operator (art 4).

2 Network regulation in the old world

The guiding principle for all economic activity in the Western society is the *market*. Network operations, such as distribution of electricity or gas, are examples of natural monopolies or market failures. For electricity distribution, the monopoly is accentuated by (i) the existence of a single supplier of the service for each customer, (ii) no substitute for the offered service and very low price elasticity, and (iii) high economic and legal barriers to market entry due to the asset-specificity and its essential importance for societal welfare. Without non-discriminatory access to the infrastructure, the operator's potential rent extraction could distort incentives for generator investments, retail competition and market efficiency, leading to losses in allocative efficiency. Without vertical separation, the network operator-generator could moreover directly distort competition by not only distorting access to information and infrastructure, but potentially also cross-subsidizing the competitive business by the monopoly operations.

In addition to the desire to incite productive and allocative efficiency, there are also non-economic reasons to impose regulation on a network industry. Attention paid to public safety, continuity of supply, public service obligations, national independence and information disclosure and integrity are examples of such objectives.

Thus, in return for granting exclusive monopoly rights, for a limited or unlimited period of time, the society empowers a regulator to act as a proxy purchaser of the service, imposing constraints on the revenues, prices and/or the modalities of the production.

Early regulatory theory largely ignored incentive and information issues, heavily drawing on conventional wisdom and industry studies. The kind of institutional regulatory economics that Bonbright (1962) and Philips (1969) represented was challenged already in the seventies with economists as Friedman, Baumol, Demsetz (1968) and Williamson (1976) questioning the organization and succession of natural monopolies. However, the main breakthrough came in the late eighties with information economics and agency theory (Holmström, Laffont, Tirole). An authoritative reading in the area is Laffont and Tirole (1993). Contemporary economic theory pursues the private goals and strategic behavior of the individual agent, with particular emphasis at the access, cost and use of information. The practical applications from this stream of research have had a profound impact on modern markets, market instruments, contracts and economic restructuring. An interesting tendency in the discussion of the challenges facing infrastructure is to revert to non-market solutions (feed-in tariffs, priority dispatch, investment subsidies, connection privileges etc) to accelerate or, in general, implement low-carbon technologies. As we will argue, in agreement with Pollitt (2009), these "intuitive" solutions are not only philosophically inconsistent with the market paradigm, they also increase complexity for actors, regulatory uncertainty and sometimes imply distortions on both allocative and technical efficiency. The current regulatory "package" in Europe is then constituted primarily of periodically reviewed high-powered regimes with partial performance assessment (mainly cost efficiency), rules for modus operandi (non-discrimination in access etc) and a set of institutional guidelines with respect to the information disclosure, organization and ownership of the regulated firms. Its effectiveness depends on the tasks and externalities it is supposed to control, past performance is only representative of future success insofar as these are of equivalent nature

2.1 Information access, task separability, independence and externalities

The properties of high-powered (incentive) network regulation depend on a number of factors, most importantly the asymmetry on cost information, task separability, role of independence and externalities.

Given that the demand for network connection is virtually inelastic, at least for electricity, the natural orientation of the regulatory policy since deregulation has been to induce cost efficiency to limit monopoly rents from the DSOs. For TSOs, the task scope already included a number of elements with high externalities and cascade effects on welfare, such as the investments in market facilitation and security of supply in general, prompting the regulators to impose relatively low-powered initial regimes for CAPEX and OPEX (Moens, 2009).

First, the cost information in a yardstick regime is related to access to a reference set of cost observations for structurally comparable operators (Agrell et al., 2005). For DSO, this condition is largely met in jurisdictions such as Germany (Agrell and Bogetoft, 2007), or Scandinavia (Agrell and Bogetoft, 2010) where data standardization and collection permit the use of econometric non-parametric models to calculate efficient costs with relatively high precision. For jurisdictions with a smaller number of operators, international datasets may potentially be used after correcting for cost and operating differences. However, the assumption of comparability relies on the previous assumption that tasks and cost drivers are uniformly applied across units, which limits the use of international data in an uncoordinated future.

Second, the current regulatory paradigm relies on high task separability between regulated segments. In the pre-Kyoto world of central generation and loosely interconnected systems, primarily for the purpose of supply security, the main network services are characterized by relatively high separability between the two vertical segments under regulation in the EU framework: distribution and transmission. The transmission system operator (TSO) is distinguished from the distributors (DSO) both in terms of scope of task (power system responsability vs local supply services), but also in terms of asset base (normally 220-380 kV vs 0.4-110 kV, respectively)[3]. The distribution networks, once unbundled from the retail operations, constitute mainly of radial passive networks with exogenously given feed-in points (substations from TSO). As will be discussed below, there is a certain concensus that the tasks related to transition towards low-carbon technologies will challenge this separability in that DSOs will be forced to replicate TSO-type tasks at lower grid levels, becoming active grid units with sophisticated local information systems and potentially even localized price information. Another challenge for task separability is the necessity to coordinate technical research and development activities in order to achieve effective and interoperable solutions to attract investments at the generation stage. Although assigned as an explict responsability for the TSOs (ENTSO-E tasks, Art 8 § 3a and § 5, EC 714/2009), we note that both regulators (OFGEM and NMa/EK) as well as DSO associations (Eurelectric) are implementing support schemes for DSO R&D.

Third, independence has been implemented primarily through unbundling of accounts for DSO, ownership unbundling only for TSOs to counter market power in generation. In the pre-Kyoto world, this could be a sufficently effective arrangement, since the unbundling guarantees information access for the DSO regulation and safeguards the central generation market, both corresponding to regulatory means to achieve welfare goals. Once again, the massive increase of decentralized generation, demand side management measures and more information intensive use of the distribution neworks changes the prerequisites for the analysis. Owners of DSO may now become major players in the growing renewables segment, with superior information about the benefits and costs of using the network, raising concerns about the objectivity of e.g. localized connection charges and equal access. This paper will explicitly investigate this issue with respect to investment incentives, but we will ignore the subsequent question on how market power in the DG retail market might be exercised.

Fourth, the externalities in the "old" world were mainly related to the TSO operations, both in terms of market functioning and environmental impact. The new situation, foreseeing wide integration of generation and load control in distribution will put the environmental externalities (CO2, space, noice, heat) in the focus of the DSO. Without adequate means of internalizing part of these externalities, it is clear that the DSO will be lukewarm concerning investments and reluctant to carry regulatory and business risk.

[3]The Scandinavian introduction of a third regulated level, the regional transmission operator (RTO) operating primarily transport services at 110-220 kV is unique.

2.2 Innovation and development activities

The radical change of the role, technology and business models for generation, distribution, transmission and load control is prompting for more than incremental development, if the tight timeframe is to be respected step-changes are likely to be necessary. However, The reduction of industry-financed R&D since the unbundling of network services and generation is significant with very few exceptions. Sterlacchini (2010) show that the R&D intensity in the sector worldwide decreased by 44% in proportion to sales (26% in absolute terms) during the period 2000 - 2007. For Europe, the figures are even more negative, -49% (R&D/sales) for all firms and -67% (R&D/sales) for a sample of the four largest private European firms (Enel, EDF, RWE, and Suez). However, only two countries in Europe provided explicit innovation or research incentives for DSOs in 2008 (Cossent et al., 2009). Jamasb and Pollitt (2008) provide a systemic analysis of the decline in research expenditure and finds it consistent with predictions taking into account privatization effects, competition and regulatory focus on cost efficiency. Although they note an increase in R&D productivity, they warn about the long-term consequences from the reduced overall R&D intensity.

As mentioned above, the European Commission has taken the lag in R&D intensity seriously enough to create a "regulatory push" through the ENTSO-E obligation to perform certain research and the provision to pass-through the related costs. However, given the economies of scale involved in the system R&D concerned and the importance of creating open standards and protocols for the technologies involved in the climate change energy sector, the provision relies also on the regulatory counterpart, the Agency for the Cooperation of Energy Regulators[4] (ACER), being able to monitor and incite effective and efficient use of the raised funds. It is puzzling that the previous R&D output was translated in such meager productivity improvements prior to deregulation, serving also as reminder to question the relationship between R&D expenditure and technological progress.

3 Review of recent work on network regulation for climate change policy

Brunekreeft and Ehlers (2005) adress specifically the problem whether the unbundling of DSO changes the incentives for DG integration. One of their contributions is to introduce the temporal (short-run vs. long-run) per-

[4] Cf. Regulation EC 713/2009 of 13 July 2009.

spective, questioning whether the DSOs are likely to experience reductions in network losses, as opposed to TSOs. Arguing that even high-powered regimes such as price- and revenue-caps for DSO in reality are regularly reset based partially on CAPEX estimates, the authors conclude that the DSO unbundling and incentive regulation are likely both to distort the timing, volume and types of DG investments made by DSOs. The results are compared to actual investment intensity among DSOs and the slow response to coordinated incentives DG-DSO.

Pollitt (2008) discusses the prospects for future network regulation, based on an ex post analysis of the UK regulatory development. Noting that most investments at both the electricity DSO and TSO level are driven by RES support schemes (such as Renewables Obligation Certificates, ROC, and the Transmission Investment for Renewable Generation, TIRG), Pollitt foresees general increases in electricity prices of about 10-15%. For the UK, the Stern review foresees a total investment need of 1% of GDP to meet carbon emission targets by 2050, thereof around 4,000 MGBP for the electricity sector resulting in a 80% reduction of the CO2 emissions by 2050. The establishment of the Office of Climate Change (OCC) in the UK must be seen as a rare and welcome sign of committment from the political principals with respect to the climate change target policy, following a period of high uncertainty and slow progress from a very low level of RES penetration. In his prospective analysis of the requirements for new network regulation, Pollitt highlights four points: (1) maintenance of the key learnings from the liberalized energy market, (2) increased process focus in regulation, lower emphasis on enduser prices as indicator of regulatory effectiveness, (3) focus at the economic realization of climate change policy measures, such as interventions, pilot projects and support schemes, (4) effective mangement of regulatory and market risk through more sophisticated risk transfer instruments. Specifically, Pollitt outlines a new regulatory model with three elements:

First, delegation of investment decisions to negotiated settlements between grid operators and users. This change in the direction of output-based regulation transforms the relationship between the network operator and the regulator from ex ante centralized bargaining to ex post auditing. Positive experiences within OFGEM for gas distribution prices and a series of international experiences analyzed by Littlechild (e.g Littlechild, 2002 and Littlechild and Skerk, 2008) using negotiated access prices, investment decisions and quality norms support this argument.

Second, more extensive promotion of competition on the grid and for its expansion (tendered expansion). By carefully reviewing explicit and implicit barriers to entry as well as strengthen the ownership unbundling requirements down to DSO level, emerging competition may be facilited for generation, energy services and heat networks.

Third, Pollitt discusses the lead role of the regulator in the climate change setting to make effective internalization of the CO2 externalities, such as in the case of investmen discounting (Weitzman, 2008), essentially acting as to assure the most economic implementation of the environmental externalities desired.

Woodman and Baker (2008) review the UK policy on DER, concluding that the current regulatory framework has been conceived to promote competition within a given energy resource, rather than the development of a more system response to socio-environmental objectives that could be addressed with DER. The recommendations for regulation focus at the removal of investment and connection barriers for DER, increased incentives for DSO participation through higher costs for losses and some alignment mechanism for investors-DSO investment decisions.

Green (2009) analyses the requirements for network regulation for three types of systems (or scopes of deregulation); retail competition (as in EU), wholesale competition (as in US and Latin America) and integrated firms (potentially nationalized, e.g. the situation in France prior to 2005). Arguing that the low-carbon policy will give rise to higher capital expenditure per energy unit delivered, through remote locations, intermittent generation and non-coinciding peaks in load and generation for renewables

Cossent et al. (2009) presents a thorough review of the state of actual national network regulation of DG in Europe and proceeds to give some regulatory recommendations. The recommendations include measures to provide economic signals for DG investors and instruments to be used in DSO network regulation. To provide efficient investment signals, Cossent el al. (2009) propose shallow connection charges and variable use of system (UoS) charges that are location-dependent, technology-dependent and cost-benefit reflective for the DG's impact on the DSO. Although the intention is to bring DSO-regulation closer to that of current TSO-regulation, including the strict unbundling from DGs, the recommendations are stay conceptual and urge for further research and development. In terms of network regulation, besides restating support for high-powered incentive regulation including the use of network service targets, the authors propose the ex ante allocation of investment budgets to DSOs with full delegation of the use of the funds. Ex post, the regulator should receive verifiable information about whether the investment has been carried out. The idea behind this proposal is to provide "policy push" from the regulator without the drawback of heavy-handed involvement in firm management. One of the model features in this paper investigates this regime. To promote investments in R&D by DSOs, Cossent et al. (2009) propose several possible means, such as activation with higher rates of return, partial pass-through of R&D expenses and mechanisms to allow capture of efficiency gains from innovations during longer (several) regulatory periods.

Vogel (2009), analyzing the investment incentives for DG of high- and low-powered regimes, argues for deep connection charges as to avoid distortions up- and downstreams in the chain. However, the final conclusion is negative when taking into account monopoly power of the DSO, asymmetric information of cost and asset utilization, as well as the intrinsic difficulty to commit to "true" high-powered regimes without glancing at the asset base. Vogel (2009) concludes in this context that "*due to technical complexity of distribution grids and the manifold information asymmetries between the involved stakeholders, a propoer design of deep charges will be very challenging to implement in to reality.*" The explicit instruction in the RES Directive to use shallow costs can then be seen as a recourse to a second-best solution in light of the problem.

Boot and van Bree (2010) reports on a wide range of policy issues related to a zero-carbon target in 2050, among those infrastructure for electricity. The authors higlight the investment consequence of low-carbon transitions into DSO networks that originally are constructed as passive networks. The role of new regulation in the view of Boot and van Bree (2010) is extended to issues such as locational pricing (also for DSO), long-term investment provisions, metering standards and innovation support. One approach forwarded in their report is the "negotiated settlement" proposed in Pollit (2009).

4 Conjecture

We have argued, with some support from the rich litterature on network regulation for low-carbon power systems, that the current paradigm will be partially outdated in the new world. However, rather than arguing along the classical Williamson range of hierarchy versus market as coordination instrument, we forward a relatively neglected stream of litterature that could help inform the theoretical foundation for future network regulation. Departing from the classical dyadic view of regulation as a two-party interaction (either regulator - firm or government - investor), the analysis above suggests that the old vertical separations between regulated segments, generation and load will be fuzzy and under continuous fire in the future. TSOs will need to understand DSO interactions, DSOs will need to operate local level control systems, intelligent load and distributed generation will call on both to control supply and demand of energy. Theoretically, the increased task complexity and asymmetry of information call for analysis of the interaction among the agents as a *team* rather than individually. Setting targets collectively increases the scope and probability that externalities can be exploited within the team, delegating the actions to the agents. Team theory also facilitates the analysis for collusive agreements among agents at various levels, both in terms of side-payments (market arrangements) and in terms of effort minimization. Indeed, the analysis of the collective team may also extend beyond the conventional frame firm-regulator and open interesting insights into the interaction and optimal organization of the multi-lateral regulatory structure itself.

Adopting the idea that network regulation may need to reconsider the boundaries and anticipate the overall effectiveness of a given policy for a societal goal, does not necessarily imply an abandon of the market as the governing principle for the energy sector also in the future. However, it does suggest that the *organization* and *delegation* of tasks to specific agents may be as important as the upfront monetary incentives offered to the agents themselves. This perspective is not very represented in the litterature, with a notable exception of Joskow and Tirole (2005)

The rest of this paper contributes to the analysis of the future network regulation by deploying a simple, stylized model of joint investment under asymmetric information to explore the policy proposals forwarded with various arguments above. Jelovac and Macho-Stradler (2002) uses a more general formulation (of the complementary case) below. They assume that there is a probability function depending on the investment levels of high values being generated, and worked with complements in the sense that the probability function is increasing, concave and with positive cross derivates. In the model below, first developed in Agrell and Bogetoft (2006), we assume discrete investments and focus at the two extreme cases of perfect substitutes or complements. A variant of the model adjusted to the setting of decentralized health care provision is found in Bogetoft and Mikkers (2008).

5 Model

We present a formal model, drawing on the DER-DSO model in Agrell and Bogetoft (2006), to investigate three prevalent scenarios; the full DSO-DER integration, a decentralized DSO scenario and centralized scenario with

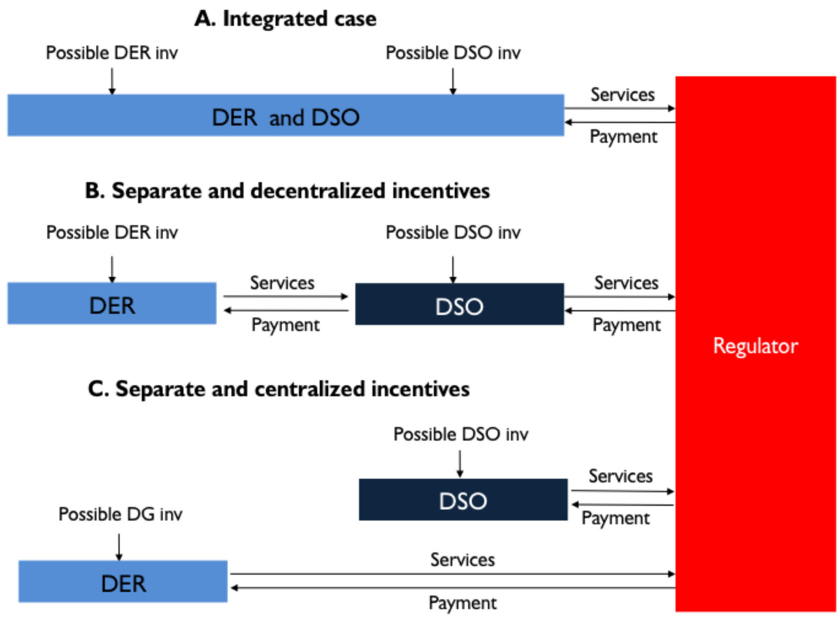

Figure 1: DER investor, DSO and regulatory organization and delegation.

parallel regulation of both DSO and DER investments (cf. Fig 1). For each scenario, we determine optimal investment policies for the DSO and DER owner under regulatory control or incentives. The evaluation criterion is the generated welfare effects, measured as the proportion of socially profitable investments that are undertaken.

The first scenario, corresponding to a situation where the unbundling requirement on the DSO is relaxed, shows the highest investment rates. The DSO internalizes the investment and the loss of investment is due to rationing by the regulator due to information problems.

The second scenario simplifies the regulation by delegation to the DSO to handle DER issues, but the results are characterized by lower investments and some distortions in the providership. Hence, the simplicity comes at a cost in this sense.

The third scenario provides the regulator with the added opportunity to contract separately with both the DSO and the DER. This arrangement brings several advantages for the investment incentives to limit costs, but it is shown that the relative profitability of investments at the two levels will crucially depend on the structure of this regulation, e.g. the role of the DER ‘bid’ in the regulation and the DSO right to initiate investments.

5.1 Investment decision

We consider a simple case with one regulator, one distribution system operator (DSO) and one investor-generator in decentralized generation or distributed energy resources (called DER below). To simplify, we study an investment opportunity assumed to be unique and indivisible, e.g. the initial investment in a technology, measurement equipment or protective device. The DSO and the DER can both achieve the effects of the investment, the costs of which are private information to the DSO and DER respectively. The investments are either substitutes or complements. One interpretation coincides with the focus in Brunekreeft and Ehlers (2005) on distribution capacity deferral, likely to be the most important direct effect (Pepermans et al., 2005). We shall now formalize in the simplest possible way without losing key properties of the situations or the solution.

5.2 Regulator

The aim of the regulator is to maximize social welfare. In a situation where a new socially desirable investments are possible at the DER and DSO levels, respectively, we may assume that the extra value generated if these investments are undertaken is $V > 0$. This social value is known and verifiable, to abstract from the moral hazard problem of fulfilling investment obligations. If the regulator – as a representative for the consumers – has to pay a total transfer T as compensation to the DSO and/or the DER, e.g. by increasing the reimbursement (revenue-cap etc) or by direct investment subsidies, the social welfare improvement is

$$W = V - T$$

The objective of the regulator is to maximize the expected value of W.

Note that it follows from the postulated objective of the regulator that he explicitly trades off the benefit derived from the costs of ensuring these. For sufficiently high values of V, however, this accommodates the objective of simply minimizing the expected costs of making the necessary DSO and DER activities. In such cases, we are close to the implicit assumption in much regulation, namely that demand is basically given and price inelastic and the aim is to fulfill demand at the least possible costs.

5.3 Network operator, DSO

The network operator (DSO) can make an investment at cost[5] $x > 0$ that is private information to the DSO. The DER and regulator only knows that the DSO's cost – to make it simple - is independent from DER's cost, and that it follows a probability distribution with density $f(x)$ and cumulative probabilities $F(x)$.The aim of the riskneutral DSO is to maximize expected revenue minus costs, i.e.

$$E\left[R - I\left(R, x\right) x | x\right]$$

where R is the revenue that the DSO is paid[6]. It may depend on his investments as well as any other possible verifiable information, including the DER investments. (We shall investigate the effects of asymmetric information not only about investment costs but also about who actually performs it in the final discussion). $I(R, x)$ is the (binary) investment decision of the DSO, one when investment is undertaken and value zero otherwise. Lastly, we note that the expectation is a conditional one. It is the expected benefits given the private information about relevant investment costs.

5.4 Investor DER

We model the generator-investor (DER) in an analogous manner. The DER can invest at a cost $y > 0$, which is private information for the DER. The investment cost y follows a probability distribution with density $g(y)$ and cumulative probabilities $G(y)$, common knowledge to all players. The DER maximizes expected revenue less cost, i.e.

$$E\left[S - J\left(S, y\right) y | y\right]$$

where S is the revenue paid to the DER. In case of a connection charge, S will be negative, and in case of net benefits from installing the equipment, say by the private benefit exceeding the installation costs, the net costs y

[5] Cost is here seen as the effective net real annuity of depreciation and capital cost in an efficient capital market as to avoid burdening the presentation with the consideration of the actual investment pattern, taxation and life cycle maintenance pattern.

[6] The actual reimbursement scheme for the DSO through allowed tariffs, recognized performance in yardstick regimes, separate by-pass of investment costs or socialized transfers from other gridlevels (transmission) is ignored here as only the behavioral effects are studied. Hence, we assume that the regulator enforces the same non-discriminatory financing pattern for this particular revenue as for any other DSO revenue, i.e. no additional distortion is introduced.

will be negative. Denote the binary investment strategy of the DER by the function $J(.)$.

6 Substitute investments

To simplify the exposition and since we consider services that can be provided at either the DSO or the DER level, we will assume that the distributions of the costs x and y are independent but identically distributed. In the case of substitute investments, the social welfare obtained is V unless none of the DSO and DER invests, i.e. $I = 0$ and $J = 0$ then it is normalized to zero.

Since both the DSO and the DER investor are rational, independent and profit maximizing, investment will only take place if it is incentive compatible for the agents. This means that the regulator anticipates the usual incentive compatibility constraints for the DSO and the DER, respectively:

$$I\left(R,x\right) = \arg\max_{\delta} \left\{E\left[R - \delta x | x\right]\right\} \tag{1}$$

$$J\left(S,y\right) = \arg\max_{\delta} \left\{E\left[S - \delta y | y\right]\right\} \tag{2}$$

Thus, both agents maximize their respective information rents with respect to the regulation imposed. In addition, individual rationality (IR) constraints must be fulfilled for each agent, since participation is voluntary. The reservation utility is normalized to zero.

$$E\left[R - I\left(R,x\right) x | x\right] \geq 0 \tag{3}$$

$$E\left[S - J\left(S,y\right) y | y\right] \geq 0 \tag{4}$$

6.1 First-best solution

Before investigating the possible solutions under asymmetric information, we observe as a benchmark the first-best solution. This is here defined as the solution when the regulator has perfect information about the costs of the DSO and DER, i.e., to invest iff

$$\min\{x, y\} \leq V$$

and in this case to implement the least costly investment level, i.e. if $x = \min\{x, y\} \leq V$, the DSO invests, $y = \min\{x, y\} \leq V$, the DER invests (in cases of ties the solution can be picked arbitrary).

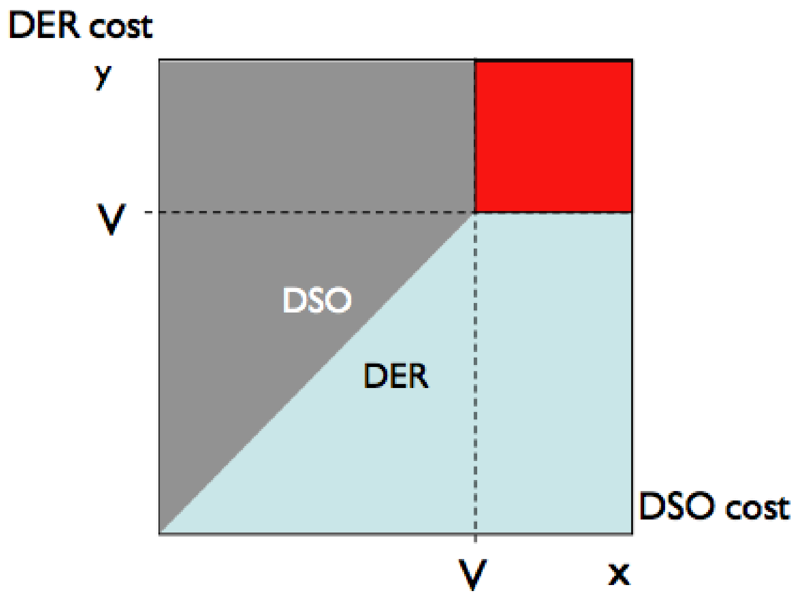

Figure 2: DSO and DER investments, first-best solution for substitutes.

The first best solution is illustrated in Figure 2 below. We see that investment takes place at the least costly level and that we only forgo investments in the red are where no level can make the investments at costs below the value V.

We will now turn out attention to three scenarios regarding the organization of the network regulation; (i) integrated DSO-DER and centralized regulation, (ii) independent DSO and DER under centralized regulation, (iii) unbundled DSO and DER under decentralized regulation.

6.2 Integrated solution

Returning to the integrated scenario in Green (2009) or the US situation, we consider a network regulation allowing the DSO to own and undertake the investment. Hence, the regulator basically faces one entity with some unknown costs z of making the investment. The integration is here defined as the legal possibility for the DSO to undertake DER investments, including harvesting gains from sale of energy at competitive terms. However, since we are assuming that (i) no non-grid related operation at the DSO, (ii) no downstream market power in the sale of energy for the DSO, the revenues resulting from the generation itself are normalized to zero as being competitively valued at marginal cost (excluding the grid impact that is explicitly modeled).

An integrated DSO-DER will of course make the investment at the least costly level, i.e.

$$z = \min\{x, y\}$$

with cumulative distribution

$$H(z) = Prob\{Z \leq z\} = 1 - [1 - F(z)][1 - G(z)]$$

Since the regulator only knows H, not the specific z, his best strategy is to make a take-it or leave-it offer to the DSO-DER entity, cf. Tirole(1988). This is a general result from mechanism design that has many applications, cf. e.g. Antle, Bogetoft and Stark (1999).

Let z^* be regulator's offer, the regulator's expected value is

$$E(W) = [V - z^*]H(z^*)$$

Since the first factor is the net benefit when investment takes place and the provider, the DSO-DER entity, is paid z^*, and the last factor is the probability that the DSO-DER actually accepts and implements the investment.

Proposition 1 *The optimal contract for the integrated case is found as the solution z^* to*

$z^* = V - [H(z^*)/h(z^*)]$

The result (see Figure 3) for the integrated case is a rationing z^* with respect to V, reflecting the tradeoff between welfare and the information rents extracted by the DSO-DER. By increasing z^*, the improvements are undertaken more often – but they are also more costly. We see that when investments do take place, they are implemented at the right level. The solution is attractive except that there are some social losses due to underinvestments (white area). Naturally, the share of investments rationed away is decreasing in the societal externality V (e.g the urgency of achieving climate change objectives) and increasing with the uncertainty related to the investment cost.

This underinvestment is a direct consequence of the mechanism to lower the information rents that the DSO-DER entity can earn. We illustrate the rationing with two examples.

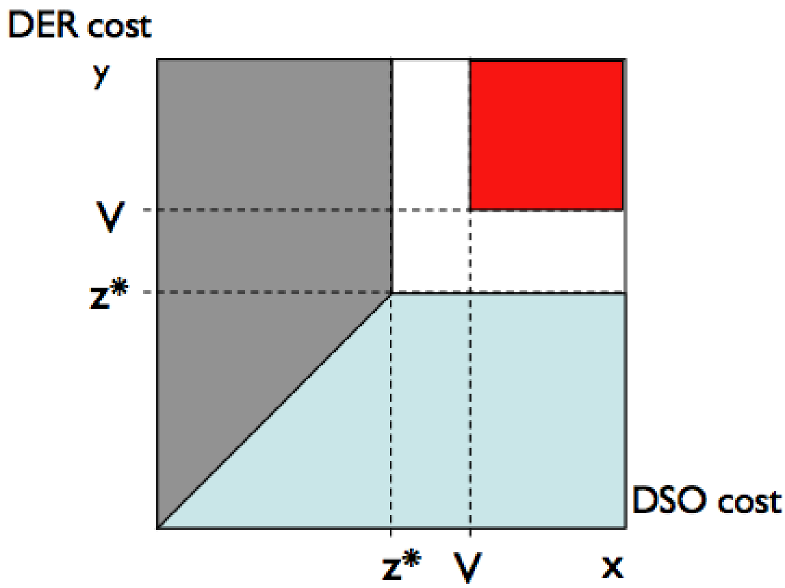

Figure 3: DSO and DER investments, integrated case, substitutes.

Example 1 *Assuming that* $V = 1$ *and that* z *follows a uniform distribution on* $[0, 1]$*, we get* $z^* = 1 - z^*/1$ *or equivalently,* $z^* = 0.5$*. Hence, the regulator deliberately forgoes half of the attractive investments in order to get the other investments at lower costs. Put more generally, the desire to share the benefits with the consumers should optimally force the regulator to forego some otherwise attractive investments at the DSO and DER levels.*

Example 2 *As another example, let us assume that* x *and* y *are independent, uniformly distributed on* $[0, 1]$*. The cumulative distribution of* $z = min\{x, y\}$ *is therefore* $1 - (1 - z)2$ *with density* $2(1 - z)$*, such that the optimal* z^* *is given by*

$$z^* = V - [1 - (1 - z^*)2]/[2(1 - z^*)]$$

For $V = 1$ *we now obtain* $z^* = 0.354$ *as investment threshold level.*

In the analysis above, we have assumed that the regulator cannot verify which of the two investments (the DSO grid investment I or the DER site investment J) the integrated entity undertakes - if any. If the investment type can be verified, e.g. by access to cost accounting details, the above solution can be improved. This situation is analyzed in details in Antle, Bogetoft and Stark (1999). Here we show than an optimal solution involves the regulator setting two cost thresholds, x^* and y^*, one for each of the two investments. The payment to the DSO will then depend on which investment is undertaken: It is x^* when $(I, J) = (1, 0)$ and y^* when $(I, J) = (0, 1)$ and 0 otherwise. The corresponding investment strategy of the integrated entity will be to pick $I = 1$ if $x^* - x \geq y^* - y$ and $x^* - x \geq 0$ and $J = 1$ if $y^* - y > x^* - x$ and $y^* - y \geq 0$, i.e. the integrated entity picks the investment to maximize information rents (and breaks ties in favor of I here). This solution will lead to less rationing. However, it will involve a coordination inefficiency in the sense that the investment with least costs may not be implemented. What matter is cost compared to the thresholds. In such a "handicapping system" the regulator would tend to favor investments that he has better information about. If the expected values of x and y are the same but the spread of the former is larger then the spread of the latter, the regulator would tend to set $x^* < y^*$ as demonstrated in Antle, Bogetoft and Stark (1999).

6.3 Unbundled DSO and DER under decentralized regulation

Assume, along the lines of the recommendations of Green (2009), Pollitt (2009), Vogel (2008), that the DSO is unbundled from the DER investor to assure independence. Further, along the lines of Pollitt (2009) and Green (2009), we assume that the regulator provides a result-based target to the DSO only, subject to direct network regulation and more informed agent than the regulator. The subsequent negotiation with the DER to achieve the coordination is then equivalent to a delegation of the regulation of DER to the DSO. I.e, the regulator incentivizes the DSO and the DSO can than decide whether to make the necessary investments or to outsource it to the DER. Before analyzing this case, we note that one can make the usual arguments for ownership unbundling (vertical separation), including the controllability of the DSO and the possibility to motivate it via relative performance evaluation (benchmarking) as it is the case in modern European regulation regimes based on revenue or price caps set partially by relative performance assessments such as frontier efficiency analyses.

In this case, the regulator can consider the DSO as the single contracting partner. Much like in the case of integrated ownership, the DSO can be characterized by its costs z of ensuring the new services with value V. In the present case, and given the separate ownership, however, the distribution of the DSOs direct or indirect cost z will reflect the internal incentive problem between the DSO and the DER. The DSO in its relation with the DER faces the same problems as the regulator does in its relation to the DSO.

The DSO can carry out the investment himself at a cost of x. Alternatively, he can try to outsource the investment to the DER level.

As before the optimal solution is found by backwards induction. Assume that the regulator has offered z^*. Two situations can now be distinguished. In the first, the DSO has costs $x > z^*$ and must therefore rely on DER to do the investment. In the second, the DSO has costs $x \leq z^*$ and can therefore make a profit by doing the necessary investments itself. Still, it may reduce costs by outsourcing if the DER has even lower costs. We shall now analyze these cases.

The first situation where $x > z^*$ is the simplest one. The DSO has only one possibility, namely to outsource. It offers DER a payment y^* so as to solve

$$\max_y (z^* - y)G(y)$$

Or equivalently using the first order characterization

$$y^* = z^* - \frac{G(y^*)}{g(y^*)}$$

That is, the DSO rations against the DER in same way as the regulator rations against the DSO or the integrated DSO-DER above. Let $y^*(z^*)$ be the solution to this problem.

The second situation where $x \leq z^*$ is one in which investment is certainly going to take place, but where the DSO can possibly improve its profit margin by the outsourcing.

Using y^{**} as a threshold towards the DER, the DSO solves for a given threshold z^*

$$\max_y (z^* - x)[1 - G(y)] + (z^* - y)[G(y)]$$

To see this observe that with probability $[1-G(y^{**})]$ the DER will decline the investment opportunity and the DSO will rely on its own investment. If, on the other hand, the DER undertakes an investment, which happens with probability $G(y^{**})$, the DSO earns the margin between the regulator's compensation z^* and its own compensation to the DER, y^{**}. Let $y^{**}(x, z^*)$ be a solution to the above problem.

Proposition 2 *The optimal contract for the unbundled DSO under decentralized regulation is to offer the investment to the DER with the threshold*

y^{**} set as the solution to

$$y^{**} = x - \frac{G\left(y^{**}\right)}{g(y^{**})}$$

Example 3 *In the case of y uniformly distributed on $[0,1]$ and $x \leq 2$, we obtain $y^{**} = x/2$.*

We can now summarize the DSO strategy. For $x > z^*$ it outsources using $y^*(z^*)$ and the DER invests with probability $G(y^*(z^*))$. For $x \leq z^*$, there is always going to be investment, either by the DER when $y \leq y^{**}(x, z^*)$ or otherwise by the DSO.

From the point of view of the regulator, this means that choosing z^* leads to DSO or DER investment with probability $F(z^*) + [1 - F(z^*)]G(y^*(z^*))$.

The regulator therefore chooses z^* to solve

$$\max_z (V - z)[F(z) + [1 - F(z)]G(y^*(z))]$$

The solution with decentralized contracting among vertical separated DSO and DER activities is illustrated in Figure 4 below.

We see that there is a general underinvestment as represented by the white area. Also, we see that the DSO tends to favor its own investments compared to DER investments. Again, this is a consequence of the rationing – in this case the DSO rations against possibly less costly DER solutions to save information rents to the DER level. Again, this represents a social loss.

Example 4 *Revisiting the previous example for uniformly distributed investment costs on $[0,1]$, we get that $y^*(z) = z/2$ and inserting this into the regulator's problem, we see that she will maximize $(V - z)[z + (1 - z)z/2]$. For $V = 1$, the corresponding first order condition is a second degree polynomial, and choosing the correct root (the left one) we get $z^* = (8 - \sqrt{28})/6 \simeq 0.4514$. This means that the regulator's trade-off between the probability of investment and the price to pay is affected – it is now possible to lower the payment with less risk of forgoing investment. Compare the Draconian rationing, $z^* = \frac{1}{2}$, that the regulator would use if only the DSO was entitled to perform the investment.*

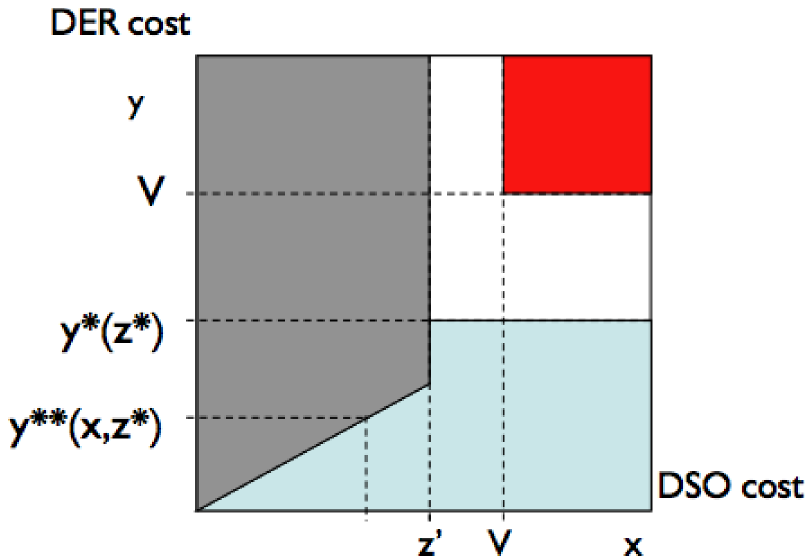

Figure 4: DSO and DER investments, decentralized regulation with outsourcing, substitutes.

The intuition is that since the DSO has the possibility to outsource the investment, the probability distribution of the least cost alternative is having more mass on lower values than the uniform distribution. Indeed, if only the DSO can provide the service, the probability of acceptance using z is $F(z) = z$ while with the DSO able to outsource also, the probability of acceptance is $[F(z^*) + [1 - F(z^*)]G(y^*(z^*))] = z + (1 - z)\frac{z}{2}$ taking into account the optimal response of the DSO in his outsourcing activities. The two situations are illustrated in Figure 5 below

In the analysis above, we have assumed that the regulator cannot monitor if the investment takes place in the DSO grid or at the DER site. This is similar to our analyses of the integrated utility. If the investment type can be observed, and if we relax the limited liability constraint into one of expected non-negative profits, it may be possible to improve the solution as demonstrated in Mookherjee (2006). The idea of such an improvement would be that the regulator could subsidize or tax the outsourcing decision to avoid the bias towards in-house investments by the DSO. Also, a penalty can be used to transfer the DSO information rent to the consumers. The

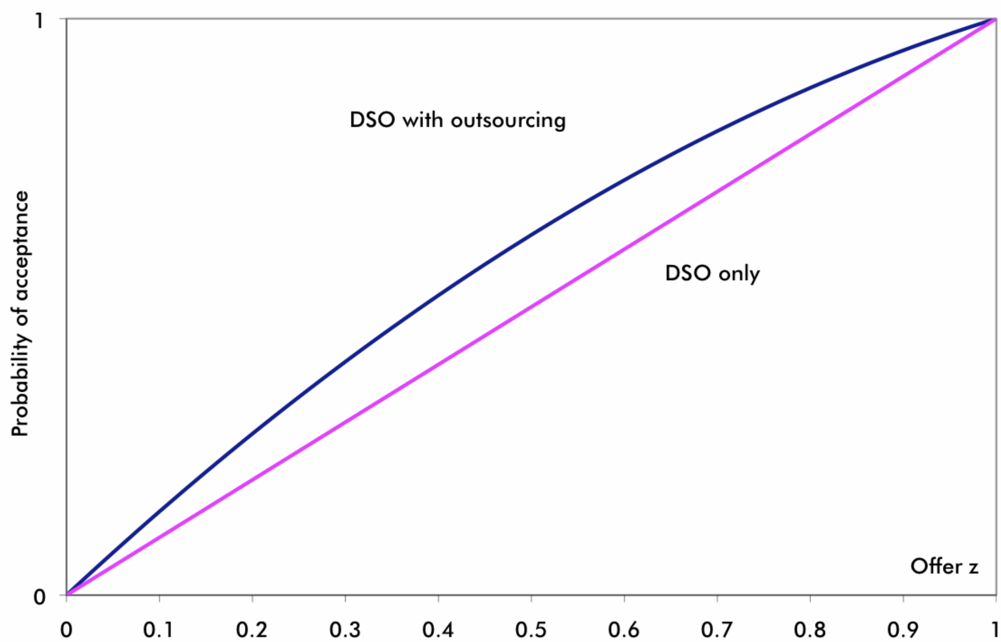

Figure 5: Probabilities of acceptance of offers z; $P(I(z))$ and $P(J(z))$.

strict outsourcing requirement of connection investments for DER to DSO grids in the Swedish network regulation is an interesting application of how this bias is addressed by simply by-passing the DSO.

6.4 Individual centralized regulation

We now turn to an organization where the regulator centralizes the regulation to both the DSO and the DER. There are two possible interpretations of this setting. In the first, the regulator uses unconditional regulation in the sense that his regulation of the DSO is independent on the reaction that his regulation has on the DER and vice versa. This is the most obvious and probably the most natural regulation in a practical setting. It sends clear signals to the DSO and the DER, but at the risk of double investments (e.g.both network upgrades and the location of DER at the end of feeder line)

The second interpretation involves conditional strategies. The regulator may use one of the parties as the default provider and the other as an optional provider. Thus, for example, the regulator could first invite the DER to do the investment and if it declines, it could turn to the DSO for possible investments. Clearly, the latter solution has some resemblances with the decentralized solution above. Still, it will be different as we shall see since the regulator does not have the information about the DSO cost that the decentralized strategies made used of.

The unconditional centralized solution requires the regulator to choose costs targets x^* and y^* that the DSO and DER, respectively, will get covered if they invest. The cost targets are set by the regulator to solve

$$\max_{x,y}(V-x)F(x)+(V-y)G(y)-V[F(x)G(y)]$$

To see this, observe that the regulator expected net benefit is the value V net of payment to the DSO if the DSO invests plus the net benefit from the DER's investments minus the value if they both invest (to balance out the double counting of values from the first two terms).

This problem leads to first order conditions

$$x^*=V[1-G(y^*)]-[F(x^*)/f(x^*)]$$

$$y^*=V[1-F(x^*)]-[G(y^*)/g(y^*)]$$

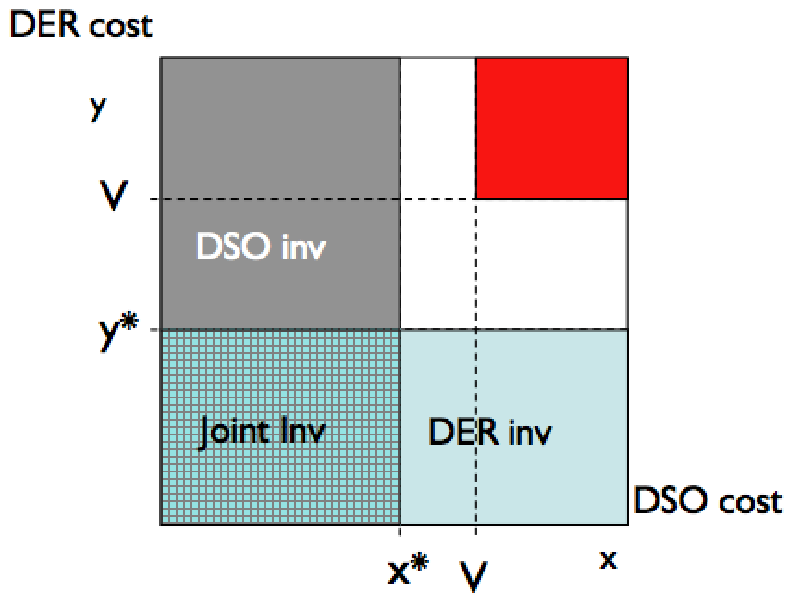

Figure 6: DSO and DER investments, centralized individual regulation, substitutes.

We see that the first order conditions have the same general structure as earlier. The regulator offers less than the possible value of the investment, i.e. he rations, to save information rents. In the present setting, the starting point is moreover not the value V but rather the discounted values $V[1-G(y^*)]$ and $V[1-F(x^*)]$ respectively, i.e. it is only the value V multiplied by the probability that the other level do not invest that counts. This reflects that the attainable value in this case since it is the value that is not already extracted by the other level. This leads to a more severe under-investment to lower the costs of double investments at low costs at both levels.

The solution is illustrated in Figure 6

Example 5 *In the case of $V = 1$ and uniform costs on $[0, 1]$, for example, we get $x^* = y^* = 1/3$. Hence, the regulator rations more harshly against the DSO and DER (using $1/3$ as opposed to $1/2$ in the case of possible investment in one level only) to lower the cost of double investments. More generally, in the case of uniform costs on $[0, 1]$ and value V, the symmetric solution is*

$$x^* = y^* = \frac{V}{2+V}$$

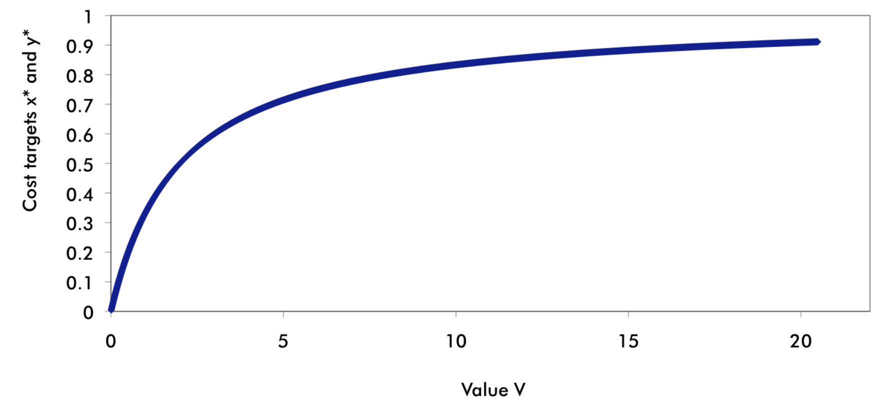

Figure 7: DSO and DER cost targets $x^*(V)$ and $y^*(V)$, centralized regulation, substitutes.

The regulator will always choose to ration - if only slightly for large values of V. This happens for the following reason: When the cost targets are getting closer to the upper limit 1, the marginal cost of rationing is declining since the forgone investments are most likely picked up by the other level. Also, the marginal benefits from rationing are increasing since the double investment problem is high when the cost targets are high and therefore the cost marginal saving in double investment costs is increasing for larger value of the targets. The cost targets are illustrated in Figure 7.

6.5 Conditional centralized regulation

Consider next the conditional centralized solution. Let us assume that the DER is the primary provider and that the DSO may be called upon to invest if the DER declines. The alternative situation with the DSO being the primary and the DER the secondary provider is similar. The conditional centralized solution requires the regulator to choose a cost target y^* that is offered to the DER and cost target x^* that is offered to the DSO if the DER has declined y^*. These targets are set to solve

$$\max_{x,y}(V-y)G(y)+(V-x)F(x)[1-G(y)]$$

To see this, observe that the regulator expected net benefit is composed of two terms. The first is the value V net of payment to the DER y^* if the

DER invest. This happens with probability $G(y^*)$. The second term is the net benefit if the DER declines and the DSO accepts. This happens with probability $[1 - G(y^*)]F(x^*)$.

This problem leads to first order conditions

$$x^* = V - [F(x^*)/f(x^*)]$$

$$y^* = V - (V - x^*)F(x^*) - [G(y^*)/g(y^*)]$$

We see that the first order conditions have a structure quite similar to the previous problems. Indeed, the optimal cost threshold for the DSO, x^*, is exactly as it would be if the DSO were the only possible provider. This is not surprising since the DSO in our setup is the secondary provider, i.e. x^* is used when DER has already declined to do the investments. In setting x^*, the regulator therefore faces the usual trade-off of lowering the price when investment takes place and at the same time running the risk of no investments. The second first order condition is also of the usual form, except that the value to be gained is lowered by the expected gains forgone by not using the DSO as the provider. That is, the value from having DER do the investment is reduced by the value of the option of using the DSO as the provider.

The solution is illustrated in Figure 8 below.

Example 6 *In the case of cost uniformly distributed on* $[0, 1]$ *and value* V *(at the most* 2*), the optimal solutions are* $x^* = V/2$ *and* $y^* = (3/8)V$.

It may seem counter intuitive that we are willing to pay more for the DSO investment that for the identical DER investment. However, this is a consequence of the rent-saving exercise. If the same opportunity is offered to both providers, the only role of the secondary provider would be to increase the investment probability. In the optimal solution, the secondary provider is also used as a competitor against the primary provider.

Proposition 3 *The conditional solution is always weakly superior to the unconditional solution.*

The see this, simply observe that the unconditional solution is also feasible in the conditional case – it is just not optimal. The disadvantage of the conditional approach from a practical perspective, however, is that it

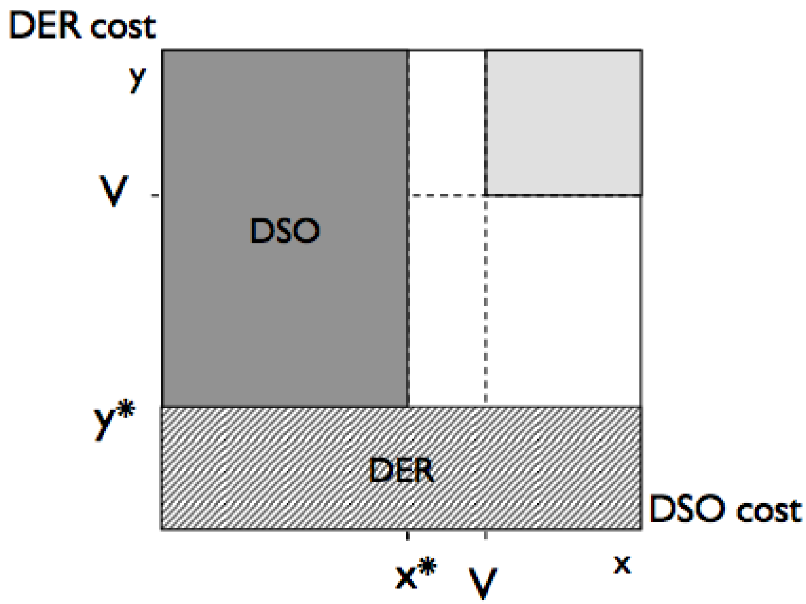

Figure 8: DSO and DER investments, centralized conditional regulation, substitutes.

takes more time using a sequential two-stage approach rather than a simply single-stage approach. Also, this would make investment planning in the DSO more difficult since it cannot plan an investment based on its own cost alone – it must await the response of the DER.

The conditional approach can be refined into a series of conditional offer: First, DER gets an offer of a relatively low cost target. If DER declines, the DSO gets an offer of a slightly higher cost target. If it declines, a new and higher offer is made to the DER and so on. Such sequential or parallel bargaining can lower the rents to the DER and DSO levels, but it would run into more serious practical problems of time needed and investment planning as discussed above. For this reason, we shall not expand on it.

7 Complementary investments

In the case of complements, the welfare effect V is obtained iff both agents invest, i.e. $I = 1$ and $J = 1$, else the outcome is normalized to zero. The case could be illustrated by the coordination of smart meters, smart grids and demand side management (DSM) for e.g. automated load control. In-

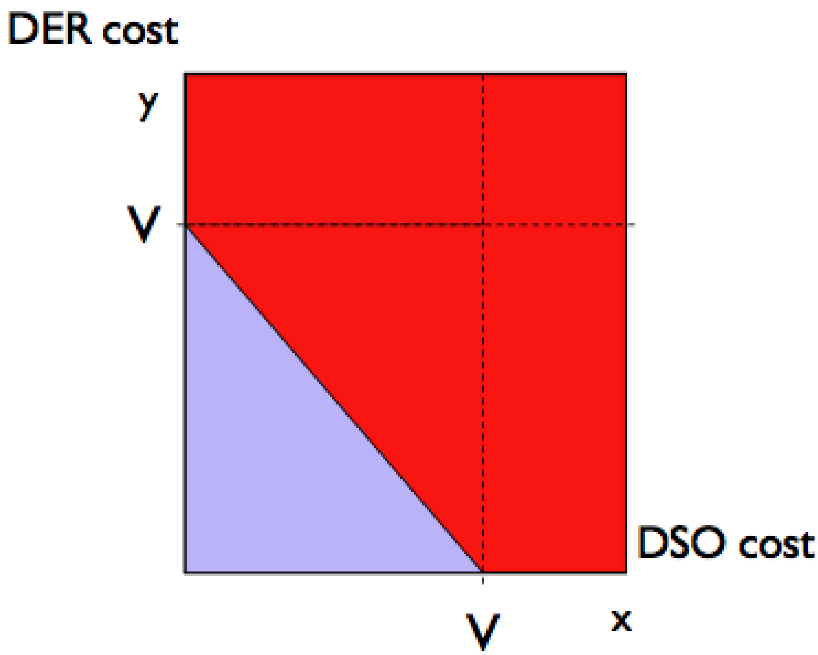

Figure 9: Investments for DER and DSO, first-best solution for complements.

stalling the DSM without meters does not exploit the externalities and the information about grid usage and real time prices, providing real-time information about grid usage and nodal prices in distribution networks without any application is useless.

The first-best solution is simply defined by the condition

$$x + y \leq V$$

The investment outcome is illustrated in Figure 9 below, the undertaken investment is in the dark grey area, the lighter grey area are socially costly investments that are rejected.

7.1 Integrated DSO-DER: centralized solution

If the DSO and the DER are integrated (or there is no asymmetry of information between the two), the total cost of the integrated entity will be

$$z = x + y$$

with cumulative distribution

$$H(z) = Prob\{Z \leq z\} = \int_0^z G(z-x)f(x)dx$$

As in the case of substitutes, the best strategy for the regulator is to make a take-it-or-leave-it offer to the integrated entity. If the regulator offers z^* to the integrated entity, the expected value for the regulator is similar to the case of substitutes

$$E(W) = [V - z^*]H(z^*)$$

Proposition 4 *The optimal regulatory contract for the integrated centralized case with complementary investment is an offer z^* found from*

$$z^* = V - [H(z^*)/h(z^*)]$$

The regulator rations, i.e. he offers less the true value of the investment V. Her offer reflects the trade-off between lowering the information rents of the integrated entity and the probability of not having the investment at all. The investment outcome is illustrated in Figure 10, where the white area denotes coordination losses, i.e. socially optimal investments that are not undertaken due to rationing.

Example 7 *For the case $V = 1$ and x, y following uniform distributions on $[0, 1]$, we get $H(z) = \frac{z^2}{2}$ for $z \leq 1$ and $H(z) = 1 - \frac{(2-z)^2}{2}$ for z in $[1, 2]$. The optimal investment threshold is $z^* = \frac{2}{3}$, i.e. investments take place only with probability $\frac{2}{9}$ whereas $\frac{1}{2}$ of the investments are socially desireable. Hence, the welfare loss corresponds to $\frac{5}{9} \simeq 56\%$ of the first-best investments.*

7.2 Decentralized regulation

In the case of decentralized regulation, the regulator offers z^* to the DSO for the combined investment. If $x > z^*$, no investment can take place. If $x \leq z^*$, the DSO can make an offer y^* to the DER investor. With probability $G(y^*)$, the DER will accept the offer. Therefore the DSO obtains y^* from solving

$$\max_y ((z^* - x) - y)G(y)$$

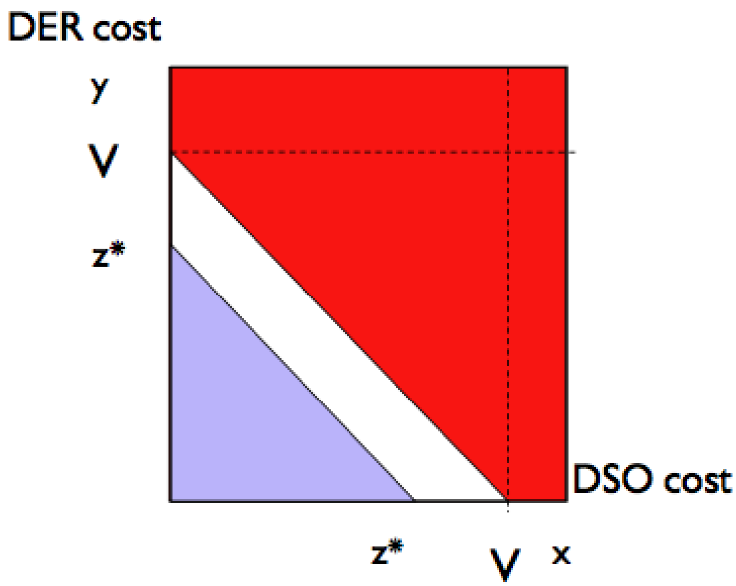

Figure 10: DSO and DER investments, integrated case, complements.

With first order condition for an inner optimum is

$$y^* = (z^* - x) - [G(y^*)/g(y^*)]$$

From the point of view of the regulator, this means that the regulator's offer z^* leads to DSO and DER investment only if both conditions $x \leq z^*$ and $y \leq y^*(z^* - x)$ hold. The first condition is satisfied with probability $F(z^*)$ and, for any given x, the second condition is satisfied with probability $G(y^*(z^* - x))$ by the independence of x and y. Therefore, the investment occurs with probability

$$H(z^*) = \int_0^{z^*} G(y^*(z^* - x)) f(x)\, dx$$

Proposition 5 *The optimal regulatory contract for the integrated decentralized case with complementary investments is*

$$z^* = V - [H(z^*)/h(z^*)]$$

The investment outcome is illustrated in Figure 11 below.

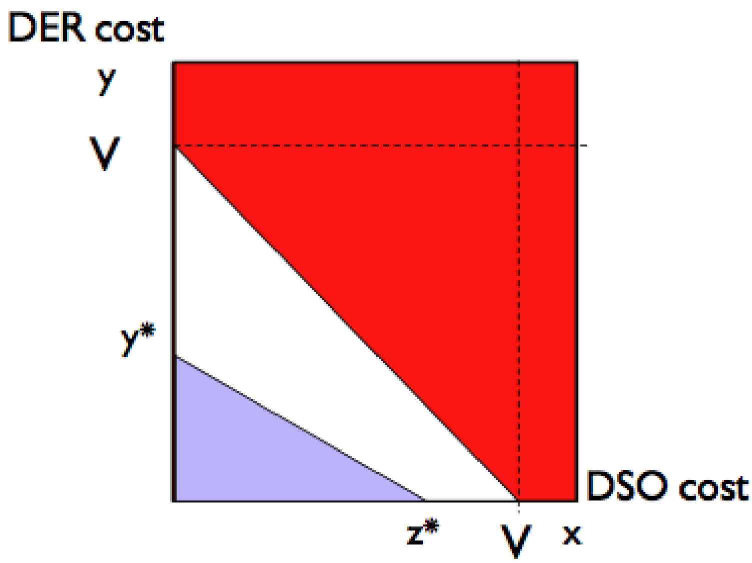

Figure 11: DSO and DER investments, decentralized case, complements.

Example 8 *For the case* $V = 1$ *and* x, y *following uniform distributions on* $[0,1]$, *we get* $y^* = \frac{1}{2}(z - x)$ *and thus* $H(z) = \frac{z^2}{4}$ *for* $z \leq 1$. *The optimal investment threshold is* $z^* = \frac{2}{3}$, *i.e. investments take place only with probability* $\frac{1}{9}$. *The social loss corresponds to* $\frac{7}{9} \simeq 78\%$ *of the first-best investments.*

The negative outcomes above for complements are robust also to the introduction of an optimal full revelation mechanism of the Myerson (1979) type, since the competition among the agents is not effective when the participation of both agents is necessary.

7.3 Individual centralized solution

In the individual centralized solution, the regulator makes offers x^* for the DSO and y^* for the DER as the solution to the problem

$$\max_{x,y} \{(V - x - y)G(y)F(x) - xF(x)[1 - G(y)] - yG(y)[1 - F(x)]\}$$

The first term represents the gain if both the DSO and DER accept the offer of the regulator. The second term represents the loss if the DER declines and the DSO accepts. This happens with probability $[1-G(y^*)]F(x^*)$. The third term represents the cost if the DER accepts and the DSO rejects the contract.

Differentiation w.r.t x^* gives us the following first order condition

$$G(y^*)[-F(x^*)+(V-x^*-y^*)f(x^*)]-[x^*f(x^*)+F(x^*)][1-G(y^*)]+y^*G(y^*)f(x^*)=0$$

From this we get

$$y^* = G^{-1}\left(\frac{x^*f(x^*)+F(x^*)}{Vf(x^*)}\right)$$

By symmetry, we get

$$x^* = F^{-1}\left(\frac{y^*g(y^*)+G(y^*)}{Vg(y^*)}\right)$$

Similar to the case of substitutes, the regulator rations to lower information rents, while he rations more than in the integrated solution to lower the loss of only one party investing. The solution can be illustrated as in Figure 12 below.

Example 9 *For the case of x, y following uniform distributions on $[0,1]$, the FOC of the objective function are $Vy-2x$ and $Vx-2y$, respectively. Thus, for $V=1$, optimal solution is $x^*=y^*=0$. The social loss corresponds to 100% of the first-best investments! For $V=2$, the solution is arbitrary for any $x^*=y^*$ in $[0,1]$ and for $V>2$ all investments are carried out.*

The intuition behind the result for the individual centralized regulation lies in the unilateral commitment from the regulator to finance the investment irrespective of the coordination in the chain.

7.4 Conditional centralized solution

To illustrate the possibility to get intermediate outcomes between those of full revelation and the individual regulation we may again consider an example of conditional regulation. One possibility in direct line with the case of substitutes is to offer the investment possibility to the DER investor and if he accepts and undertakes the investment, to offer the investment also

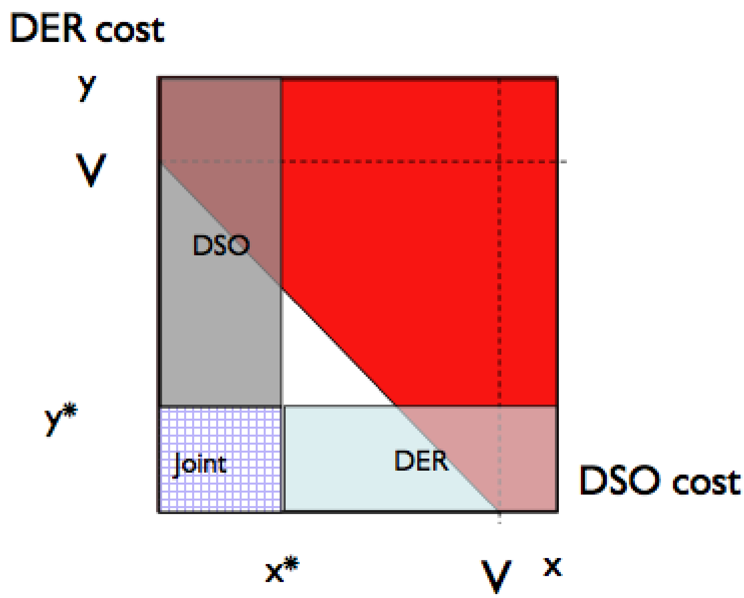

Figure 12: DSO and DER investments, centralized individual regulation, complements.

to the DSO. The advantage of this arrangement compared to the individual regulations above is that we can avoid having the DSO invest without the DER investing. We can however not avoid that the DER invests but the DSO refuses to do so as well. The outcome following such an arrangement will therefore often be that the regulator should refrain from any investments to begin with much like in the case of individual regulation.

To get a different outcome, therefore, we will here assume that the regulator can make conditional regulations in the following sense: She offers (simultaneously) a separate contract to both the DSO and the DER. An accepted contract by one party is only valid if the other party also accepted his contract. Therefore, in the unconditional centralized solution, the losses due to acceptance by only one party do not occur.

The regulator therefore solves:

$$\max_{x,y} \{y(V - x - y)G(y)F(x)\}$$

with corresponding first order conditions

$$x^* + y^* = V - \frac{F(x^*)}{f(x^*)}$$

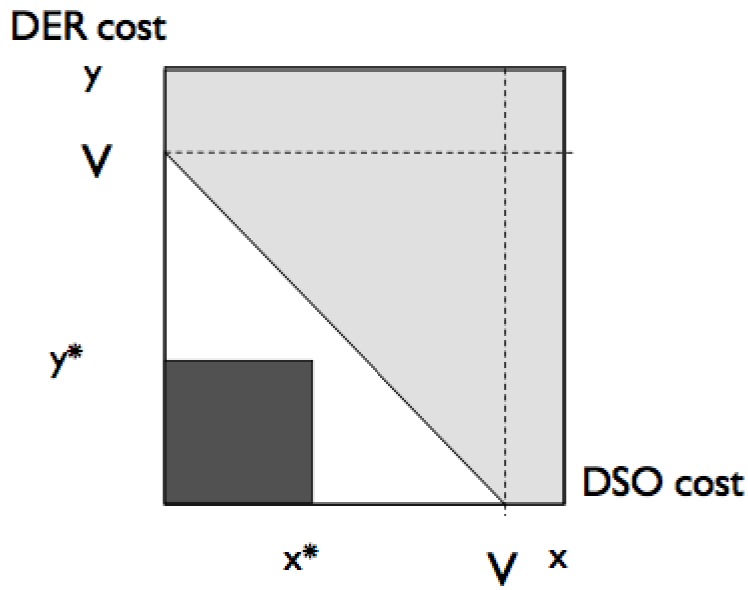

Figure 13: DSO and DER investments, centralized conditional regulation, complements.

$$x^* + y^* = V - \frac{G(y^*)}{g(y^*)}$$

This solution is illustrated in Figure 13 below.

Example 10 *For the case of* $V = 1$ *and* x, y *following uniform distributions on* $[0, 1]$*, we obtain* $x^* = y^* = \frac{1}{3}$*. Investments take place with probability* $\frac{1}{9}$ *as in the decentralized regulation. The social loss corresponds to* $\frac{7}{9} \simeq 78\%$ *of the first-best investments.*

The intuition for the equivalence between the conditional centralized regime and the decentralized regulation is also found more generally in Melumad et al. (1995), where delegated contracting like our scheme replicates the second-best solution obtained through centralized contracting. Moreover, Macho-Stadler and Perez-Castrillo (1998) explore the properties of the delegated contracting when side-payments and collusive agreements between agents are possible. Effectively, when the possibility of collusive behavior is independent of contractual organization, the two regimes are equivalent also under moral hazard.

Table 1: Outcomes, uniform example, substitutes

Regulation	x^*	$P(I,J)$	$E(W)$	Rationing	Misallocation	Double invest
First-best	–	1.000	0.667	No	No	No
Integrated	0.354	0.583	0.376	Yes	No	No
Centralized	0.500	0.750	0.417	Yes	No	No
Decentralized	0.451	0.575	0.316	Yes	Yes	No
Centralized individual	0.333	0.556	0.333	Yes	No	Yes

Table 2: Outcomes, uniform example, complements

Regulation	x^*	$P(I,J)$	$E(W)$	Rationing	Misallocation	Double invest
First-best	–	0.500	0.167	No	No	No
Integrated	0.667	0.222	0.074	Yes	No	No
Centralized	0.667	0.222	0.074	Yes	No	No
Decentralized	0.667	0.111	0.037	Yes	Yes	No
Centralized individual	0.000	0.000	0.000	Yes	Yes	Yes

8 Conclusion

To summarize the findings, we table the outcome for the case of uniform costs $[0,1]$ and welfare $V = 1$, the situation for substitutes in Table 1 and for complements in Table 2, respectively.

In the case of substitutes, the centralized solution is the preferred option as it avoids misallocations (i.e., lowest cost investment is implemented) and does not involve useless duplicated investments. There is still losses associated with the outcome, namely due to the rationing. Rationing in the sense that not all investments with cost below the value to the consumers are undertaken is part of the solution since it enable the regulator acting as a substitute consumer to lower the information rents he has to pay.

For complements, the same finding as above for substitutes is relevant. A centralized regulation can here replicate the second-best solution obtained from an integrated DSO internalizing all effects.

If – for reasons that may go beyond the scope of the model – the two levels are separated (unbundled), we can foresee two possible organizations of the regulation. In the first, the regulator contracts with the DSO that has the option to outsource the investments. In the other, the DSO and DER are contracted individually by the regulator.

The best separated outcome is the first one, i.e. it involves decentralized regulation: only the DSO is contracted directly and the possible regulation of DER is delegated to the DSO. The advantage of this approach of having decentralized regulation of DER is that the DSO has private information about its own costs and that it can use this information when deciding how to incentivize DER. Nevertheless, this setting leads to less overall investment – at a higher cost to the consumers. Two types of inefficiencies are present, namely rationing and some misallocation of investment among the two levels. The DSO favors its own investments since outsourcing generates costs of asymmetric information.

When the regulator contracts directly with both levels, the outcome is less efficient – there will be rationing and double investments, i.e. in some cases, the DER and DSO levels will both end up investing even though this is unattractive since the investments are substitutes. This can be partly circumvented if the regulator uses conditional regulation such that the offer to one level depends on the response of the other level. The latter however may be a difficult approach in practice since it requires time to first offer the investment to a primary provider and next to a secondary provider if the primary provider declines.

In short, therefore, from the point of view of substitute investments, the regulator will prefer an integration of the DSO and DER activities – and if this is not possible, it would prefer a regulation of one of the levels leaving the control of the other to the directly regulated level.

Of course, this ranking of the different organizational and regulatory solutions may conflict with other objectives that we have ignored, including the need to incentivize cost reductions at the DSO level in general via relative performance evaluations like in a high powered revenue cap (CPI-X) regulation.

Taking the broader perspective, we provide two policy results, for the design of future incentive network regulation and for the organization of network services, respectively.

First, the results show that in the presence of increased importance for discrete delegated investments with high asymmetric information, the optimal regulation of future network services should remain a high-powered incentive regulation – with an inclusion of the investment driver as part of the service description of the DSO. An example of where this is used in yardstick design for electricity DSO is Bundesnetzagentur in Germany, cf. Agrell and Bogetoft (2007). The DEA frontier model specification used in the regulation includes variables for the subscribed capacity for decentralized generation into the network, divided by voltage level, as cost drivers.

Second, the network regulation should if possible be centralized to one agent with verifiable investments and no delegated or conditional rights. This means that the "negotiated agreements" are likely not a long-term solution for the network regulation in the future. This result can be directly compared to that of Joskow and Tirole (2005, section 5) where the question of merchant investments in transmission can be delegated to the contracting parties, in their case two potential investors. For both complementary and substitute investments, the authors reject the applicability of the Coasian theorem (unless mitigated by long-term contracting) since a number of assumptions are not fulfilled; (low) transaction costs, complete information, presence of all stakeholders, absence of free-riding, absence of hold-up of potential losers. In the current situation, we note that several of these conditions are violated also in the case of the local DSO-DER bargaining. The DSO is naturally in informational advantage, there are high transaction costs involved to adequately describe and contract on the externalities involved on and off the grid, the future grid users are not represented at the negotiation although likely to assume the investment if made by the DSO, future investors in generation can free-ride on infrastructure in e.g. control equipment and protection etc.

Finally, it should be noted that the discussion and the model is oriented to a specific policy issue: the provision of investment incentives for CAPEX increases in order to accomodate and fully utilize future low-carbon energy resources. This is made without neglecting the importance of assuring the development of technologies for the future energy system, including the potential establishment of CCS installations and networks that in themselves may give rise to questions of network regulation that do not share these properties.

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