Bremer Energie Institut

Bremen Energy Working Papers

Paperseries No. 10

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In Cooperation with Jacobs University Bremen

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Vorgeschlagene Zitierweise/ Suggested citing:
Autor, (Jahr), "Titel", Bremen Energy Working Papers No. #, Bremer Energie Institut.

Improving investment coordination in electricity networks through smart contracts

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September 28, 2011

Abstract: Smart contracts based on voluntary participation and optionality can be a low transaction cost solution to implement locational signals in distribution networks and thereby avoid network investment. This paper examines the efficiency properties of smart contracts. Based on a three-node example network we show that cases exist in which smart contracts can achieve a pareto-improvement compared to the status-quo even with voluntary participation. With the pareto improvement at least one party is better of under a smart contract without worsening the situation for anyone else. We note that this requirement is very restrictive and leaves significant potential for efficiency improvements by smart contracts untapped. We then discuss the implementation of smart contracts with incentive regulation. There are two main tasks for the regulator: allowing network operators flexibility to offer such contracts and incentivizing network operators to do so.

Keywords: network investment, distribution networks, locational pricing, smart contracts

1 Introduction

Distribution network operators face several challenges that result in increased investment needs. Apart from ageing assets an important factor is the significant volume of distributed generation that is built in distribution networks. The increase in distributed generation can cause congestion since lines have not been built for large bottom-up flows. Most often distributed generation is renewable or combined heat and power generation which may add intermittency. Yet, this generation is an important aspect of climate policy and likely to increase even further. These developments change the operational paradigm of centralized, controllable generation and top-down power flow. It requires investments in order to upgrade transformers and guarantee voltage stability. Furthermore, the development of smart grids[1] brings about a more decentralized and active user structure. There are for example prosumers that are both producing and consuming energy or electric vehicles that present a locationally and temporally variable load.

The diversity of users feeding in and taking off electricity from the grid needs to be managed to guarantee system stability at every point in time. Since lines only have limited capacities local clustering of load or generation can cause congestion. The exact effects depend on the local network conditions, size, type, location as well as the utilization pattern of the installation. The impact can go in both directions: new demand or distributed generation can relieve network stress and defer investments at some locations while it increases network investment need at others (Piccolo & Siando 2009, Ackermann 2005). Hence, the coordination of network and network users in space and time can release efficiency potentials and avoid network investment. Large parts of distribution networks date back to the 1970's. They are about to reach the end of their lifetime and replacement becomes necessary. Therefore coordination of network investments efficiently with the development of network users and thereby reduce the necessary investment could directly have a positive effect.

Currently network expansion policies are often oriented towards maximum demand. Once a situation with insufficient network capacity is observed, the network will be reinforced or expanded. In economic terms this may be inefficient since the network is extended to prevent any possible constraint. Essentially there is no balancing between cost and benefit that stops network expansion at the efficient level. Especially in cases where the

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1 We use smart grids to refer to electricity distribution networks with a high share of decentralized generation, an active demand side, and additional flexibility via storage. An information and communication infrastructure connects the diverse actors in the smart system and enables advanced control and coordination approaches. Recently smart grids are also discussed with respect to gas grids (see e.g. Hinterberger & Kleimaier 2010) or concerning the transmission networks (see e.g. Battaglini et al. 2009).

capacity limit is only exceeded in few occasions per year management of generation or demand might be more efficient than network investment.

However, currently users do not have an incentive to take network conditions into account. Distribution networks in many countries rely on uniform pricing and network cost are often socialized to demand (see Brandstätt et al. 2011a). Prices do not convey signals on the network conditions and network impact remains an externality to network users. Locationally differentiated pricing can be a tool to internalize the network conditions and signal network users their network impact. The price system can help steering them according to network needs. Locational signals can appear in the network or energy charge as well as in a combination of both. As discussed in Brandstätt et al. (2011b) in distribution networks the realization of general tariff plans that include locational differentiation is fraught with problems. We proposed smart contracts instead as a tool to send locational signals in a low transaction cost and flexible way. Smart contracts are voluntary agreements between the network operator and network customers, i.e. demand, generation, and storage that realize a trade-off between investment into the grid and into demand and generation. We argued that smart contracts are more beneficial in smart distribution networks than locational signals in a general tariff plan for the following reasons (Brandstätt et al. 2011a, b):

- Network operators can flexibly design these contracts to better adapt customer behavior to network capacities when this is cheaper than network investment.
- More refined pricing structures have to emerge in smart grids anyhow and we already observe developments in this direction. Location would be one additional aspect that might be beneficially added to tariff design.
- Smart contracts do not require a reform of the entire pricing system and need only little regulatory intervention. This implies that the implementation is more likely and less burdensome than a complete overhaul of the pricing scheme.
- Participation in smart contracts is voluntary. If combined with a default tariff, this ensures that customers are protected against exploitation by the network monopolist in the negotiation of a smart contract.

An improvement of the overall situation and incentive compatibility of smart contracts (as the key notion of smart contracts is voluntary participation starting from the current state of affairs) have not been shown yet. In this paper, we provide a numerical example where smart contracts improve some stakeholders without worsening the situation for any of the others. This illustrates how smart contracts can achieve a pareto-improvement and are thus also incentive compatible and improve overall economic efficiency. Hence with a small change in the regulatory framework towards allowing more flexibility in contract design at least one party can become better off while no party is harmed. Importantly, network operators need incentives to pursue smart contracts as an alternative to network expansion. This implies that they should be entitled to part of the benefits from the avoided investment. It is the task of the regulator to a) allow network operators the flexibility to design smart contracts and b) to incentivize network operators such that they carry out efficient network investment and will offer smart contracts where investment can better be avoided.

The paper is organized as follows: Section 2 briefly reviews locational pricing in distribution networks and outlines smart contracts as favorable option for implementation. Section 3 presents the model and two specific cases of smart contracts. The results and the implications for the regulatory framework are discussed in section 4. Section 5 concludes.

2 Locational pricing in distribution networks

In theory locational pricing is a powerful tool to steer network utilization and thereby avoid investment. Locational signals that appear in the energy price are known as locational marginal pricing or nodal pricing. This method is successfully applied e.g. in US transmission networks. Congestion is reflected in prices at both sides of the constraint: lower energy prices at the generation dominated side make feed in less attractive and incentivize consumption while higher prices at the other side do the opposite. Alternatively, the locational signal can appear in network charges. In this case areas with scarce network capacity would exhibit higher charges for generators thereby dis-incentivizing new utilization. Areas with spare capacity would feature comparably lower tariffs. Price signals are expected to steer users away from areas with scarce capacity or incentivize generation close to load (see e.g. Ofgem 2009). This can enhance system efficiency for example by avoiding capacity expansion and reducing losses. While nodal spot pricing needs explicitly designed markets, locational network pricing requires at least regulatory approval of the tariff methodologies to ensure that locational differentiation is not used to conceal other discriminatory intentions. Hence, both locational energy and network pricing are general tariff plans and require regulatory reform. In contrast, smart contracts are an instrument to set locational incentives with little regulatory intervention and high flexibility.

2.1 Locational network pricing

Locational signals in network charges can appear in connection charges and use-of-system (UoS) charges. The connection charges typically cover the costs of lines, transformers and other equipment needed to connect a new user to the grid. Connection charges are called shallow if the network user pays only the direct cost of connecting to the next connection point in the existing grid. Charges that also include the reinforcement that becomes necessary in other parts of the existing network are called deep charges. An example for a deep component is the upgrade of transformers or lines in the existing grid to enable the distribution of additional electricity generated at a newly connected site. In areas with scarce network capacity, new connections likely trigger network investment. Deep charges reflect this effect making congested sites less attractive.[2] Deep charges are a powerful tool for cost-reflective locational signals. However, implementation is difficult because the determination of fair and transparent deep charges is a non-trivial exercise as further described in Brunekreeft et al. (2005).

UoS-charges cover the running cost of the network such as losses and balancing energy. Typically UoS-charges are not locationally differentiated but average based for each voltage level and differentiated further by the extent of use. This practice does not reflect the actual condition of the network at a specific site. However, locational differentiation in distribution networks has been achieved for example in the UK where incremental cost pricing includes the expansion cost of the network into the UoS-charges. It thereby introduces a long run perspective (Li et al. 2005). If siting at a certain location defers network investment, charges are low. In contrast, charges are high, if new connections cause network reinforcements. Hence, the charges reflect the urgency of network investment.

2.2 Locational energy pricing

Energy prices that incorporate the locational dimension are known as locational marginal prices (LMP) or nodal spot prices (Hogan 1992, Schweppe et al. 1988). Nodal prices display the marginal cost of supplying load at each node. In addition to standard spot prices nodal spot prices reflect the topology of the system and take into consideration the transportation cost of electricity, i.e. losses and congestion. Zonal pricing is a less detailed variant of locational energy pricing. It differentiates prices by zones rather than per node (for further considerations see e.g. Björndal & Jörnsten (2001)).

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[2] See for a more detailed discussion e.g. Woolf, 2003.

Nodal spot pricing is considered to send first best signals for short-term system optimization, i.e. for operation (Stoft 2002, Hogan 1992). Long-run signals are weak since nodal prices do not reflect fixed network cost. Although they lead in the right direction, they are insufficient to guide efficient investment decisions (Brandstätt et al. 2011b, Brunekreeft et al. 2005). Furthermore, today most retail customers are on uniform tariffs and therefore do not receive nodal price signals.

2.3 Smart Contracts

Smart contracts are additional agreements to the standard regulated, possibly uniform tariff and thus represent a way to implement targeted locational signals without the need to reform the general tariff plan. Network operators could offer contracts to flexible customers in order to make use of their flexibility for the benefit of the network. This is in line with developments expected in the course of the transformation towards smart grids: While the technical potential for inclusion of load and generation into distribution system management is enormous, the respective actors need to be incentivized to participate. Prices and contracts are the way to achieve just this. In view of efficient network investment, these smart contracts can obviate the need for more explicit locational signals in network or energy general tariff plans.

Importantly, smart contracts are voluntary; customers can always fall back on a default tariff. This ensures that no negative distributive effects compared to the baseline have to be expected. After all, market participants would only accept a smart contract if it was for their better and if the benefit of the contract exceeds the transaction cost. In other words: some network users will improve their situation by entering smart contracts. For other network users things remain the same. This resembles the findings of Willig (1978) who showed that non-linear tariffs can achieve a pareto-improvement compared to a uniform price above marginal cost. Optionality is the key component to improve not only consumers in aggregate but each individual. In Willig's work network users can choose between a two-part tariff and the uniform price. In a similar way network operators can design smart contracts in addition to a regulated default tariff. Relevant characteristics of customers that might be targeted by smart contracts are for example location, size, and flexibility. The most relevant target group for smart contracts may be the bigger distribution network customers such as commercial customers or generators or user clusters since their impact is more pronounced and the relative transaction cost are lower.

3 Model

The concept of smart contracts is based on the assumption that network users will only enter the voluntary contract if this is beneficial and otherwise will stick to the regulated tariff. This guarantees that the contracting parties can only improve since this is the precondition for offering respectively entering the contract. The analysis in this paper will show exemplarily that this is possible even without harming any other stakeholder in the system who cannot influence whether or not the contract takes place.

We use a three-node example network to illustrate our case. The model illustrates how smart contracts can achieve pareto-improvements compared to a situation with uniform pricing and an obligation to expand the network. Our starting point is a situation in which one line in the network is congested. The benchmark solution to congestion is network expansion. We then present several opportunities to relieve congestion with smart contracts avoiding network investment and analyze the effects. The pareto-improvement considers the changes in surplus for the following agents:

- network operator
- generators (at different nodes)
- load (at different nodes and including storage where applicable)

The network operator is responsible for system operation and network investments. Network operators recover the cost for network operation and investment from demand customers via use of system and connection charges. In our benchmark case, socialization of cost is to demand side customers only and generation does not pay use of system charges. We assume a market price P_E for electricity above generator marginal cost C_G. Practically speaking, this reflects a contribution to fixed cost of capital and formally speaking this ensures a positive outcome for generators when producing although we assume constant marginal cost (making the difference to indifference).[3]

Moving to a system with smart contracts creates additional financial flows in both the network operator's expenses and the network customer's income. With the aim to steer behavior and avoid network investment, the network operator could grant a rebate or pay a bonus to its customers. We assume that even if existing generation is not charged connection charges, nonetheless, they could receive a bonus via a smart contract.

[3] Usually, marginal cost is assumed to be increasing, which would leave generators with a positive outcome even under marginal cost pricing. For our purpose this would only make calculations more complex without adding additional insights. For our purpose of illustrating how smart contracts can achieve a pareto-improvement, the assumption of constant marginal cost seems sufficient

symbol	meaning	unit
P_E	energy price	€/MWh
P_N	network charge	€/MWh
I_N	network expansion cost	€
D	total demand	MWh
D_n	demand at node n	MWh
D_{Sn}	demand from storage at node n	MWh
G_n	generation at node n	MWh
G_{Sn}	feed-in from storage at node n	MWh
G_{Cn}	curtailment at node n	MWh
C_G	generation cost	€/MWh
P_{E_peak}	energy price in peak periods	€/MWh
P_{E_off}	energy price in off-peak periods	€/MWh
U	utility of electricity consumption	€/MWh
α	reduction on network charges for demand at desirable locations	€/MWh
β	rebate on network charges for storage	€/MWh
δ	premium for curtailed generation	€/MWh
γ	bonus for network (connection) at desirable sites	€/MWh
ω	reduction of the utilization value at second choice location	€/MWh

Table 1: List of variables in the model.

3.1 The problem

For illustration purposes we simplify the problem to a three-node network in which the cheapest dispatch to supply the given demand at a certain point in time is not compatible with the physical capacities of the network as shown in Figure 1.

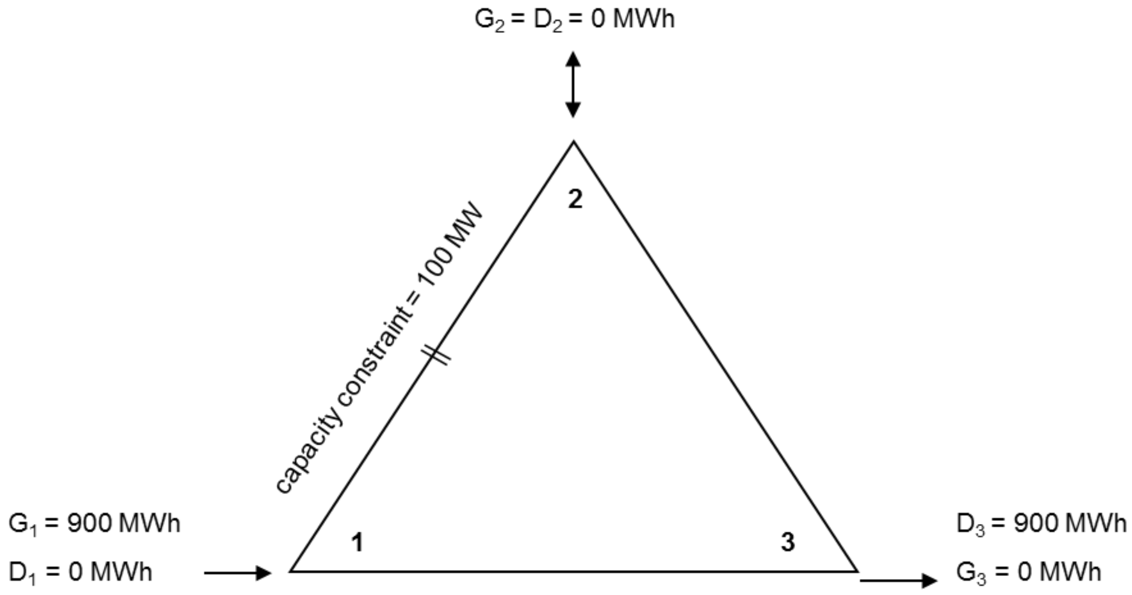

Figure 1: Infeasible dispatch under given capacity constraint.

Assume that generation at node 1 is renewable generation (e.g. wind) which receives priority feed-in. Assume further that in cases where renewable generation cannot feed-in because of limited network capacity the network operator is obliged to expand the network[4] and that the line between node 1 and 2 is limited to a maximum capacity of 100 MW. Generation at node 1, $G_{1,}$ is 900 MWh and load at node 3, $D_{3,}$ amounts to 900 MWh. Node 2 is balanced between generation and demand and therefore appears as net flow of 0. Although the situation is generally balanced, it is technically not feasible as the flow between node 1 and 2 would exceed the capacity of the existing line: the current dispatch causes congestion.[5] The situation can be solved with network expansion (copper solution). Alternatively, a different constellation of feed-in and take-off can ease the situation. Controllable generation leaves the network operator with the freedom to regulate feed-in. Alternatively, in case load at node 3 is comprised of electric vehicles that are potentially flexible in time and location of consumption, the network operator can influence take-off. At any case the network operator

[4] Such assumptions are inspired by real-world renewable support schemes as they can be found for example in Germany. In Coasian terms, the network users have the property right of unconstrained network access.

[5] Following Kirchhoff's laws, in an AC system, the 900 MW injected in G1 splits 600 MW between G1 and D3 and 300 MW G1-G2-D3, which is not possible due to the line constraint.

would need to incentivize network users to change their behavior and thereby defer network investment. We present selected solution scenarios in turn.

3.2 Reference case: Network expansion

The "investment solution" to capacity constraints in the network is the expansion of the respective lines as depicted in Figure 2. This will serve as a reference case for the smarter solutions presented below.

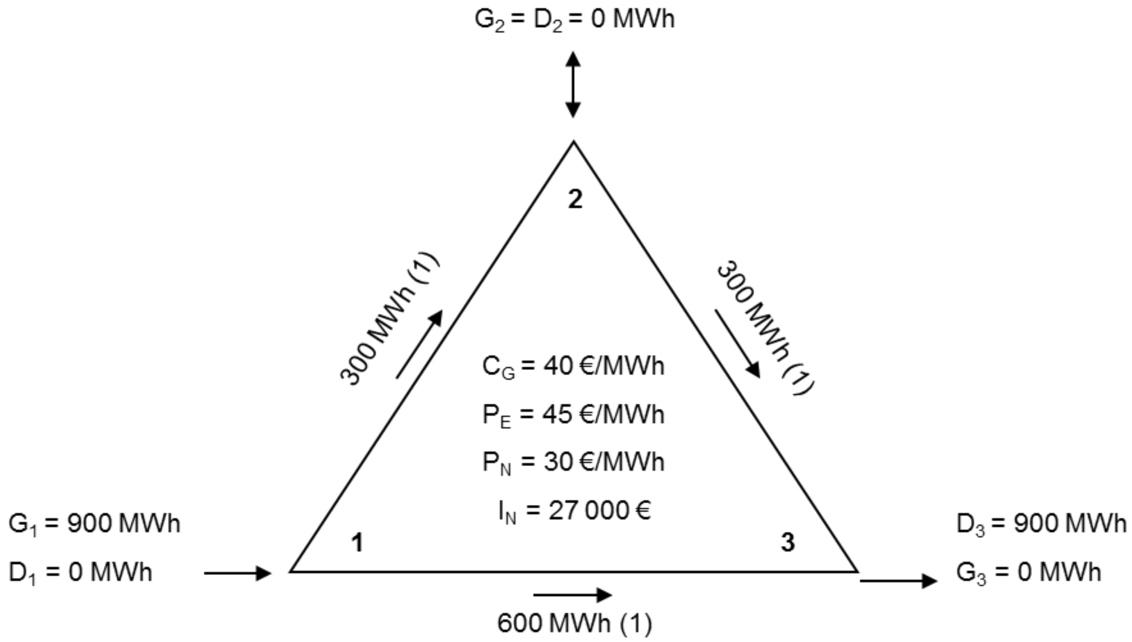

Figure 2: Reference case: network expansion.

Expanding the capacity of the line from 1 to 2 with 200 MW to a total capacity of 300 MW relieves the congestion. Assume network expansion cost I_N to be 27000 €.[6] Whenever smart contracts are able to relieve congestion at a lower cost than the necessary network investment, they can achieve an improvement compared to the status quo. Assume furthermore that the costs of network expansion are allocated to network users via network charges.[7] Socialized to demand only this results in a network charge P_N of 30 €/MWh for demand customers.[8] Additionally, customers pay an energy charge P_E of 45 €/MWh which in this case covers generator cost C_G at 40 €/MWh and includes a generator surplus of 5 €/MWh. We assume that consumption of electricity provides the customer with a certain utility U (which is assumed to be sufficiently large to keep consumers connected).

[6] The precise number of 27000 € has no meaning; it is a fictive value of normalized network investment.

[7] The socialization can incorporate both consumers and generation. Since the common practice in distribution networks is the socialization to demand only we assume the generation/load-split to be 0/100.

[8] This abstracts from other components in the network charges such as losses, maintenance, and personnel.

Income distribution in the reference case which is used as a benchmark to evaluate the performance of smart contracts is displayed in Table 2.

	Profit functions	Pay-off
network	$P_N \cdot D - I_N = \frac{30€}{MWh} \cdot 900\ MWh - 27000\ €$	0 €
generation (G_1)	$(P_E - C_G)G_1 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 900\ MWh$	4500 €
generation (G_2)	$(P_E - C_G)G_2 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 0\ MWh$	0€
demand (D_3)	$(U - P_E - P_N) \cdot D_3 = \left(U - \frac{45€}{MWh} - \frac{30€}{MWh}\right) 900\ MWh$	$U - 67500$ €
demand (D_1)	$(U - \omega - P_E - P_N + \alpha) \cdot D_1$ $= \left(U - \frac{0€}{MWh} - \frac{45€}{MWh} - \frac{30€}{MWh} + \frac{0€}{MWh}\right) 0\ MWh$	0 €
storage (D_S)	$\left(P_{E\_Peak} - P_{E\_Off}\right) D_S = \left(P_{E\_Peak} - P_{E\_Off}\right) 0\ MWh$	0 €

Table 2: Income distribution in the reference case.

3.3 Alternative: Network investment deferral

In cases where the maximum capacity is needed only for very few occasions, network expansion is not efficient (Stoft 2002). Alternatively, changes in generation and demand can solve the constraint and defer network investment. Assume that the network regulation is such that if the investment costs are deferred the network operator can keep (part of) the avoided expenses. As a consequence, the network operator could make use of these avoided expenses to incentivize network users to change behavior such that network investment is deferred. This can be achieved by smart contracts for both, demand and generation side. The network operator, being best informed about problems in his network can target those customers that have a relevant impact on the network. It seems plausible that, if left freedom to do so, he will offer efficient contracts to defer network investment.

3.3.1 Alternative 1: Smart contracts for generation

One solution is to relieve congestion with purely generation oriented measures. For the illustration of this we draw on the example from Figure 1 and Figure 2. A shift in the generation pattern as illustrated in Figure 1 can relieve congestion as follows: partial curtailment of the generation at node 1 (G_1) to 600 MWh and feed-in of an additional 300 MWh of generation at node 2 (G_2). Generation at node 1 might be prioritized generation and curtailment politically difficult.[9] What is essential here is that we assume generators enter

[9] This is a realistic assumption for many countries with feed-in systems e.g. Germany.

curtailment agreements voluntarily, whilst retaining the right to produce (priority feed-in under fixed feed-in tariff). That means they continue to receive the P_E for voluntarily curtailed power and receive a premium δ on top.[10] The δ incentivizes generators to accept such a contract when otherwise they could be indifferent between producing or not. Brandstätt et al. (2011c) illustrate how such voluntary curtailment for generators can be beneficial for the system while not negatively affecting climate goals.

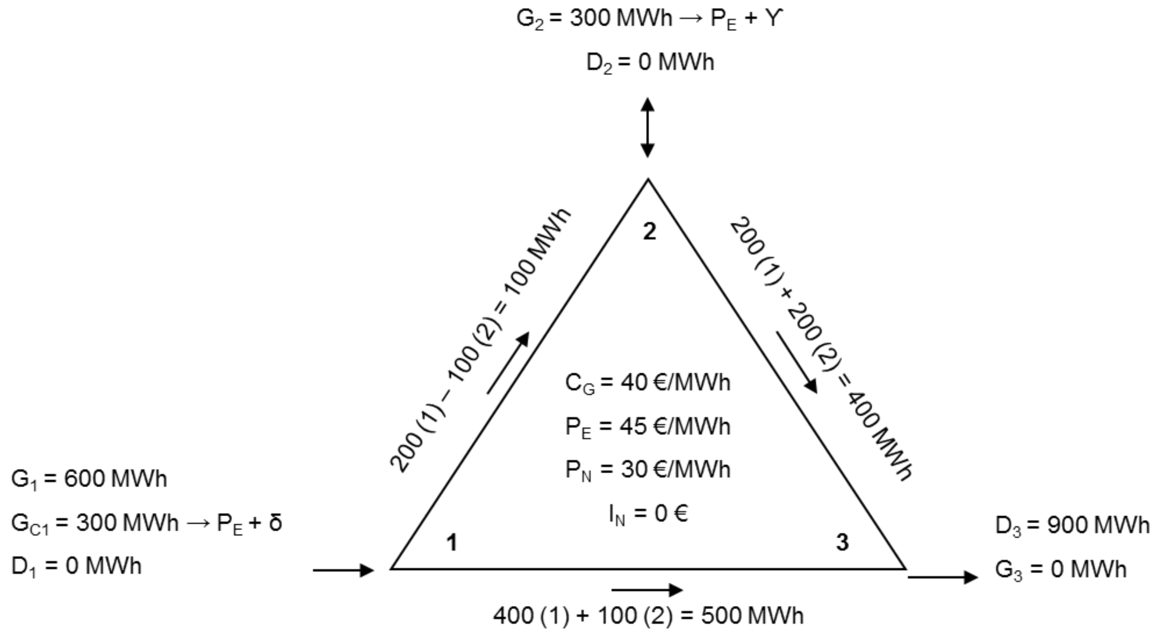

Figure 3: Alternative 1: Smart contracts for generation.

However, in the long run the curtailment premium creates perverse incentives. If generators in congested regions receive a premium for not producing this attracts generators to connect in already constrained regions because these regions promise additional income from curtailment contracts. Hence, the locational signal for generators goes in the wrong direction. Note, that this is the discussion of perverse incentives known from counter trade: curtailment compensation leads to improved investment conditions 'behind' the constraint (see e.g. Dijk & Willems 2011). Under the presence of perverse incentives, the network operator would be worse off with the price differentiation under smart contracts: the constraint would increase in the course of time and expansion will become even more necessary. If the network operator foresees increased investment needs resulting from smart contracts, he will always invest directly in network expansion and smart contracts will not

[10] Typically the continued payment of P_E in case of curtailment would be adjusted to the variable cost of the generator. The underlying logic is that for example fuel cost does not need to be compensated for since in case of curtailment no fuel is spent. For reasons of simplicity we assume that C_G is only fixed cost that incurs regardless of actual electricity generation, so that curtailment compensation with the full P_E is justified. This assumption is realistic for example for photovoltaic or wind generation.

work. Alternatively, perverse incentives could exist but are compensated by a mechanism that prevents *new siting* at already congested locations such that smart contracts remain feasible. This can be relatively lower network charges at desired locations by paying out a bonus γ as explained above. Also, available sites for new generation in the congested area might be scarce making the problem relatively small in itself since the limitation on available sites constrains the additional generation capacity that can be built.[11] Alternatively, the network operator might want to incentivize storage in situations where smart contracts with curtailment compensation create perverse incentives for generators. This can also relieve the constraint (see below section 3.3.2) by enabling the needed flexibility and it does not incur the risk of worsening the constraint.

Although theoretically cost-reflective (positive) network charges can be calculated such that they equal out exactly the "false" positive incentive at congested locations, this is not possible in a situation where generators do not pay network charges. Furthermore, it rules out a pareto-improvement since it would deteriorate the situation of generators that did not pay before. Therefore we assume a network bonus, γ, that is paid at non-congested locations to make these more attractive vis-à-vis congested locations. The bonus can in principle be granted as one-time rebate on the connection charge or as ongoing payment for feed-in. The γ serves to steer new users to locations with spare capacity rather than to congested locations which promise curtailment compensation. The additional incentivized feed-in at node 2 needs to make up for the curtailed generation at node 1 (G_{C1}).

The additional generation at node 2 can be from new or existing generators. If existing (conventional) generators at node 2 did not produce before because of congestion created by RES-E production, curtailment enables this generation to become active. It does not receive the network bonus γ because these generators already made the siting decision and paid for their connection. They do not need additional incentives to site at node 2. Intuitively, the bonus should only be granted to newly connecting generators. However, this might raise concerns on price discrimination. In particular if the bonus is a per-unit payment and thus affects marginal costs and might thus distort competition. This speaks in favor of bonus payments to all generators at favorable locations without differentiating between existing and new installations.

The following Table 1 gives an overview of the income balance for the different actors in a system with smart contracts as described above.

[11] Hence, the customer groups are not exogenous at each location. This violates the condition of "no arbitrage" which is necessary for an effective pareto-improving non-linear pricing scheme, as known from the literature on price discrimination.

	Profit functions
network	$P_N \cdot D - (P_E + \delta)G_{C1} - \gamma \cdot G_2$ $= \frac{30€}{MWh} \cdot 900\ MWh - \left(\frac{45€}{MWh} + \delta + \gamma\right) 300\ MWh$
generation (G_1)	$(P_E - C_G)G_1 + (P_E + \delta)G_{C1}$ $= \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 600\ MWh + \left(\frac{45€}{MWh} + \delta\right) 300\ MWh$
generation (G_2)	$(P_E - C_G + \gamma)G_2 = \left(\frac{45€}{MWh} - \frac{40€}{MWh} + \gamma\right) 300\ MWh$
demand (D_3)	$(U - P_E - P_N)D_3 = \left(U - \frac{45€}{MWh} - \frac{30€}{MWh}\right) 900\ MWh$

Table 3: Income distribution for alternative 1.

Summing up, we note that smart contracts that induce voluntary curtailment require the network operator to pay P_E plus an additional δ. Furthermore, also new generation at node 2 has to be paid a bonus γ on top of the regular remuneration. While the remuneration for produced electricity is obviously paid by final customers that consume the energy, the smart contract payments appear at the network operator side. These additional expenses have to be lower than the network investment that can be avoided. Otherwise it would be better to expand the network. Hence, if smart contracts should be cheaper than network expansion, the additional expenses for δ and γ may not exceed 45 €/ MWh. Generators are always better off because they receive a bonus payment on top of the market price in both locations: at node 1 for curtailment and at node 2 to incentivize siting. The following table details the payoff of alternative 1 in comparison to the reference case.

	Payoff Base Case	Payoff Case 1	improvement
network	$0\ €$	$13500\ € - (\delta + \gamma)300\ MWh$	$if\ (\delta + \gamma) < \frac{45\ €}{MWh}$
generation (G_1)	$4500\ €$	$16500\ € + \delta \cdot 300\ MWh$	$always$
generation (G_2)	$0\ €$	$1500\ € + \gamma \cdot 300\ MWh$	$always$
demand (D_3)	$U \cdot 900\ MWh - 67500\ €$	$U \cdot 900\ MWh - 67500\ €$	$0\ €$

Table 4: Improvement with alternative 1.

3.3.2 Alternative 2: Smart contracts for demand and storage

Another solution to relieve congestion is the use of demand-side oriented measures and storage. In smart systems this aspect will be of particular relevance. The increasing complexity of the system resulting from the diversity of actors, bi-directional power flows and intermittent generation is expected to require extensive flexibility. Storage can provide such flexibility. Extending the definition of storage beyond pure physical storage, it can also incorporate demand flexibility or demand response as “virtual storage”. While conventional storage and demand are immobile and can only provide flexibility at a certain location, electric vehicles are mobile and can therefore potentially better address locational problems.

Storage

Assume the problem results from the priority feed-in of wind at node 1 that congests the network. Instead of curtailing wind, the network operator can use storage capacity at node 1 to relieve the constraint. It offers the additional benefit of unloading the storage in times of low wind generation thereby leveling the feed-in profile of wind generation. Note that storage appears as additional demand at node 1 (D_{S1}) in our example. Importantly as in alternative 1 this requires additional feed-in at node 2. Figure 4 displays the new situation.

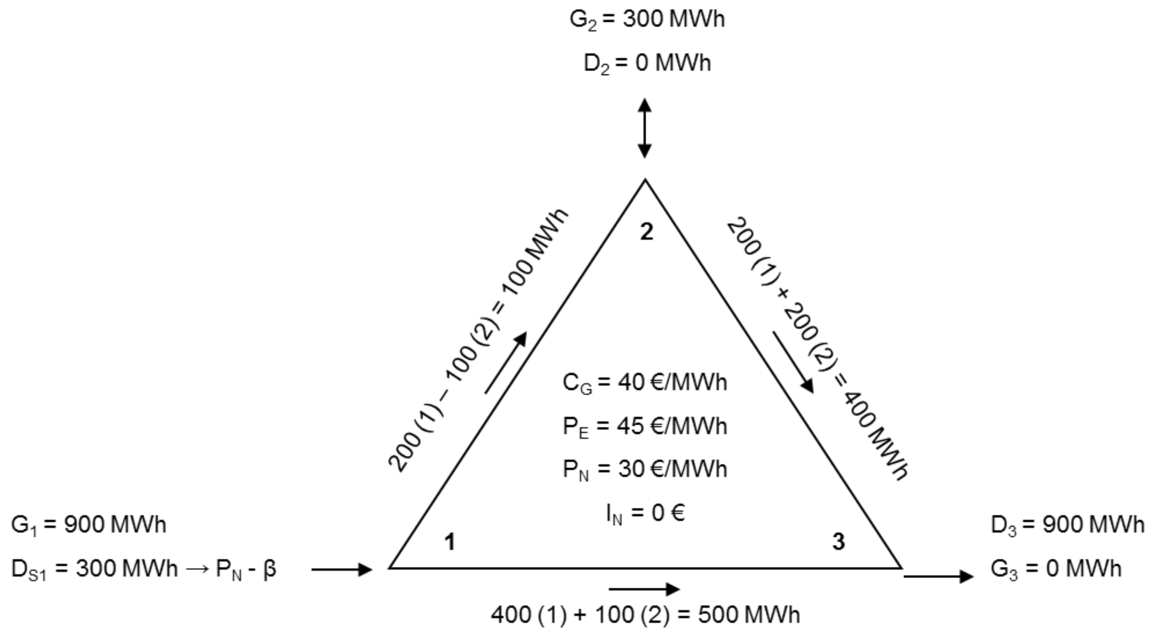

Figure 4: Alternative 2a: Smart contracts for storage.

Storage operators buy electricity to resell later at a higher price. They do not incur network charges for the stored energy.[12] We abstract from losses and other operation cost. Hence, the difference between buy price and sell price determines the income of the storage operator. In order to incentivize flexibility in the system the network operator grants storage facilities a bonus of β. Compared to the reference of network expansion this is feasible as long as β is less than 90 €/MWh. Table 5 details the payoff functions for all actors in case 2b.

[12] This assumption is realistic. For example the German government decided to exempt new storage from paying use of system charges in the context of needed flexibility. Paying network charges would represent a significant barrier for new investments in storage.

	Payoff function
network	$P_N \cdot D_3 - \beta \cdot D_S = 900\,MWh \cdot \frac{30€}{MWh} - \beta \cdot 300\,MWh$
generation (G_1)	$(P_E - C_G)G_1 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 900\,MWh$
generation (G_2)	$(P_E - C_G)G_2 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 300\,MWh$
storage (D_{S1})	$\left(P_{E\_Peak} - P_{E\_Off} + \beta\right) D_{S1} = \left(\frac{45€}{MWh} - \frac{45€}{MWh} + \beta\right) 300\,MWh$
demand (D_3)	$(U - P_E - P_N)D_3 = \left(U - \frac{45€}{MWh} - \frac{30€}{MWh}\right) 900\,MWh$

Table 5: Income distribution for alternative 2a.

While the situation of the generator at node 1 remains unchanged the generator at node 2 incurs an additional profit from producing when he was not producing in the reference case. Since storage receives a bonus (β) that was not available in the reference case its situation improves as well.

Note, that this situation is a snapshot view only. While storage acts like demand in some hours it would feed power back into the grid in other hours and thereby appear as producer. The question then is: what happens in this second period? Assume storage is built with the particular purpose of leveling out intermittent wind production. Storage can take up wind production when feed-in exceeds capacity and feed back to the grid when wind production is very low. Hence, we assume a base case with only 300 MWh wind feed-in. This requires 600 MWh of generation at node 2 to supply demand which is still at 900 MWh. Figure 5 displays the base case for the second period (left) and the respective changes with storage (right). Table 6 compares base case and alternative 2a over both periods.

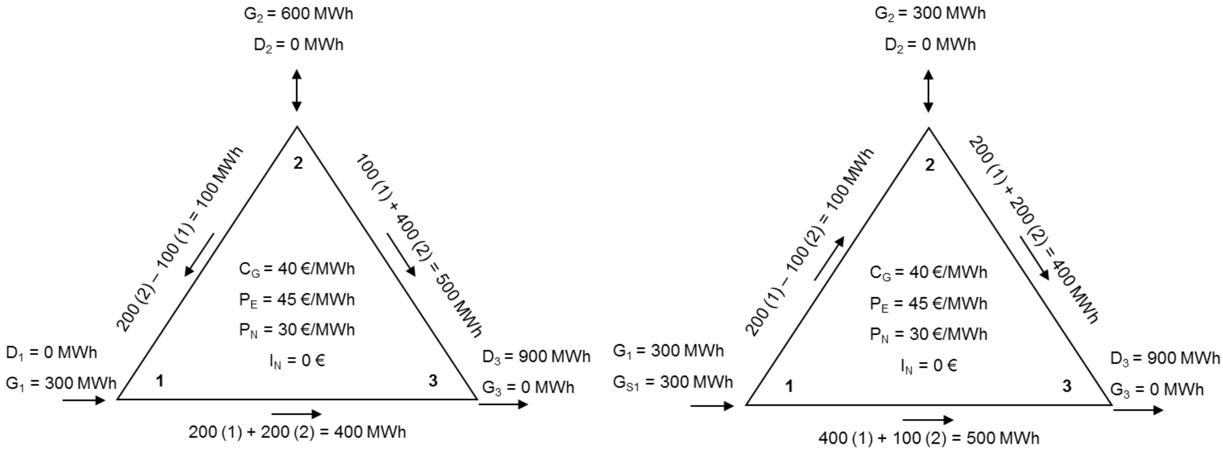

Figure 5 Alternative 2a: Second period – storage feeding back to the grid.

	Payoff Base 1st+2nd Period	Payoff Case 2a 1st+2nd period	Improvement
network	$0\,€ + 27000\,€$	$54000\,€ - \beta \cdot 300\,MWh$	$if\ \beta < \frac{90€}{MWh}$
generation (G_1)	$4500\,€ + 1500\,€$	$4500\,€ + 1500\,€$	$0\,€$
generation (G_2)	$0\,€ + 3000\,€$	$1500\,€ + 1500\,€$	$0\,€$
storage (D_S)	$0\,€$	$\beta \cdot 300\,MWh$	$if\ \beta > \frac{0€}{MWh}$ [13]
demand (D_3)	$2(U \cdot 900\,MWh - 67500\,€)$	$2(U \cdot 900\,€ - 67500\,€)$	$0\,€$

Table 6 Improvement with alternative 2a – 1st and 2nd period.

It can be seen that feed-in from storage reduces the need for additional generation at node 2. Hence, while these generators benefitted in period 1 when they could produce more in comparison to the base case, they can produce less in period 2. Both effects level out.

We note that the overall effect is positive if periods with low generation at node 1 occur that allow storage to feed back into the grid without causing additional constraints. If this is not possible, storage can be to the detriment of generation at node 1 since feed in from storage would compete with G1. In this case generation needed to be curtailed and the generator at node 1 would be worse off than in the base case with network expansion. Hence, driving the criterion of pareto-improvement to the extreme, G1 should receive curtailment compensation as in alternative 1. It is obvious that at some point this may render smart contracts undesirable because numerous compensations not only in the current but also in future periods arise. It is then a question of how far the criterion will be understood and what will be taken as baseline. The pareto-improvement is a good starting point as it minimizes reluctance against those arrangements since no player is harmed. Even if it were relaxed voluntary and optional smart contracts realizing efficiency improvements are still possible improving only the parties involved in the contract but not necessarily everyone else. Also the above the situation of storage competing with existing generation may be a virtual problem. In many cases, with fluctuating generation storage can feed back to the grid without the need for curtailment. There may be only some extreme hours in the year that cause local network congestion.

[13] Note that the economic viability of storage depends on the spread between peak and off-peak price unless there are other benefits (such as leveling out wind production). , For the storage to receive a positive pay-off, $(P_{E\_Peak} - P_{E\_Off} + \beta) > 0$. Furthermore, since we assume prices to be equal in 1st and 2nd period, storage does only make profit from β but not from the price spread.

Locational demand shift

The problem of congestion on the line between node 1 and 2 results from concentrated demand at node 3 in combination with concentrated generation at node 1. A locational shift of demand from node 3 to 1 where electricity is produced would relieve the system stress. Therefore, as an alternative to network expansion, some of the electric vehicles could be incentivized to load at node 1 instead of 3 as displayed in figure 5.

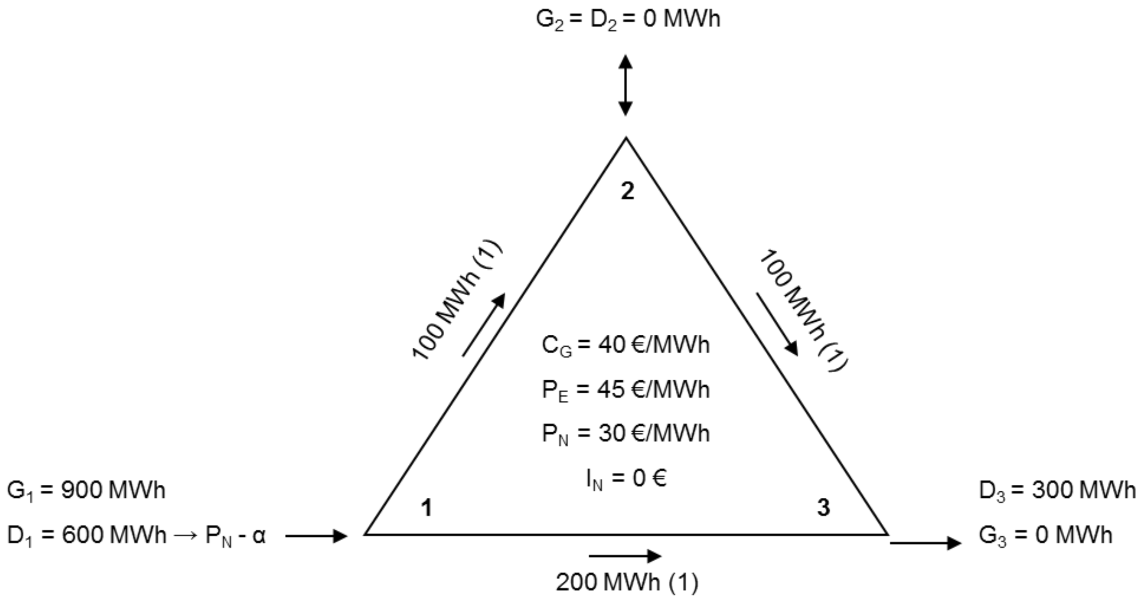

Figure 6: Alternative 2b: Smart contracts for locational demand shift.

The incentives in this case can come from an additional payment of α for load at node 1. With a composite tariff of network and energy charges, a payment related to the MWh consumed is the same as lowering the electricity cost (and thereby the fuel cost for the EV) by α, even if in reality it is a reduction of the network charge. However, it does not necessarily need to be MWh-based, it may just as well be a flat standing charge that only varies by location. Since demand originally located at node 3 we must assume some benefit from locating at node 3 rather than 1. This reflects in a change of the utilization value by ω. The benefit α paid for charging at another location must make up for the foregone benefit ω when locating at node 1. Otherwise demand would not enter the respective smart contract. For this alternative the income distribution is as described in Table 7.

	Profit function
network	$P_N \cdot D - \alpha \cdot D_1 = \frac{30€}{MWh} \cdot 900\ MWh - \alpha \cdot 600\ MWh$
generation (G_1)	$(P_E - C_G)G_1 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 900\ MWh$
generation (G_2)	$(P_E - C_G)G_2 = \left(\frac{45€}{MWh} - \frac{40€}{MWh}\right) 0\ MWh$
demand (D_1)	$(U - \omega + \alpha - P_E - P_N)D_1 = \left(U - \omega + \alpha - \frac{45€}{MWh} - \frac{30€}{MWh}\right) 600\ MWh$
demand (D_3)	$(U - P_E - P_N) \cdot D_3 = \left(U - \frac{40€}{MWh} - \frac{30€}{MWh}\right) 300\ MWh$

Table 7: Income distribution for alternative 2b.

As long as the premium α paid to demand is below 45 €/MWh the network operator retains a benefit as compared to network expansion in the reference case. The situation of generators and the remaining demand at node 3 is not altered. For the demand that changes location from node 3 to node 1 an improvement is possible as long as the payment of α outweighs the utility loss of ω. This is summed up in Table 8 as follows.

	Payoff Base Case	Payoff Case 2b	improvement
network	0 €	$27000\ € - \alpha \cdot 600\ MWh$	$if\ \alpha < \frac{45€}{MWh}$
generation (G_1)	4500 €	4500 €	0 €
generation (G_2)	0 €	0 €	0 €
demand (D_1)	$U \cdot 900\ MWh - 67500\ €$ (for D_1 and D_3 together)	$(U - \omega + \alpha)600\ MWh - 45000\ €$	$if\ \alpha > \omega$
demand (D_3)		$U \cdot 300\ € - 21000\ €$	0 €

Table 8: Improvement with alternative 2b.

4 Discussion

4.1 Efficiency of smart contracts

The three alternatives to network expansion presented here represent applications of smart contracts where all involved parties improve and all affected parties at least remain indifferent if not even improve as well. Hence it becomes clear that it is possible to achieve a pareto-improvement through smart contracts. However, what does this mean for (economic) efficiency? The first thing to note is that a pareto-improvement logically always secures an efficiency-improvement. However, what happens to efficiency in cases where a pareto-improvement does not exist?

Firstly, there may be cases where smart contracts for load shift or storage are too expensive or the perverse incentives on generator siting cannot be compensated profitably from avoided investments. In those cases the network operator has to expand the network and incur the capital expenditure. We would expect that in most cases where network expansion actually takes place, it is actually the efficient outcome. If network expansion is the cheapest option, it will be hard to incentivize others for the more expensive alternative.

Secondly, it should be stressed that for the examples in this paper we made two important assumptions on the possible smart contracts:

a) they should represent a pareto-improvement
b) they cannot include positive charges to generators

Both these assumptions set limitations that cause some inefficiency, since the network operator can only set positive incentives, which is always additionally costly. While this is justified when compensating generators for positive external effects, it excludes the possibility of charging for negative external effects. The claim for a pareto-improvement takes into consideration effects on *all* actors in the system. This can be a very restrictive concept. Numerous smart contracts are possible that improve efficiency while causing negative effects on third parties. If the situation for network operator and contracting party improves they can conclude such a contract on a voluntary and optional basis if allowed. A limitation to only such contracts that represent pareto-improvements might be too restrictive. It narrows the potential for efficiency enhancing smart contracts. Furthermore, the criterion of a pareto-improvement will be hard to enforce. In practice, the criteria of voluntary participation and optionality will apply to active players (those who make choices; incentive compatibility only applies to active players); all those who do not choose do not benefit from optionality and voluntary participation. Unless some actions are explicitly prohibited their interests may be adversely affected: following the arguments above, this impedes the criterion of pareto-improvement, but may actually increase economic efficiency.

4.2 Incentives to defer investments within the regulatory framework

Above we have argued that voluntary and optional contracts offered by the network operator to network users may increase overall system efficiency by avoiding avoidable network investment; this in turn reduces the need for the regulator to implement a price system. This approach raises the question whether the network operator actually has incentives to avoid inefficient investment. In other words, which incentives does the regulatory framework set?

The current regulatory framework in Germany already contains such incentives. Within the regulatory period, the system is incentive-based and allowed revenues are fixed. It is only in the review for the new period that allowed revenues are adjusted to costs. This means that within the regulatory period firms will have incentives to reduce expenditure and these avoided investments translate into profits. In addition, there is an automated network expansion factor for DG, meaning that newly connected decentralized capacity raises the revenue constraint with a fixed factor. Again, this is incentive-based and sets incentives to avoid inefficient investment. In addition to these components, inefficient investment affects the benchmarking results negatively and will thus increase the X-factor, again setting correct incentives. The effects change with the cost-based review, which implies the classical Averch-Johnson effect. If companies make profits with an increased capital base, they will want to make investment. The overall effect depends on the length of the regulatory period, which determines how long companies can retain profits from reducing expenditure.[14]

The analysis above extends to approaches to repair the investment problem. If the time-delay problem is solved by an automatic cost-pass-through of investment, like e.g. in Austria, the incentives to avoid inefficient investment are low. These incentives will then only be counterbalanced by benchmarking.

Ex-ante investment allowances are more promising. They do not suppress necessary investment (as they allow the revenue constraint to be raised) while at the same time they retain the incentives to avoid inefficient incentives as companies can keep the avoided expenditure. If it is considered that it is unreasonable that the companies retain 100% of avoided expenditure, a sliding-scale mechanism would split the savings between consumers and companies. This would weaken the incentives but nevertheless retain some of its power. We should note however that investment allowances are a problem within the setting of the German regulatory framework due to the large number of networks,

Another institutional issue concerns system governance or more specifically network unbundling. With network unbundling any kind of internalization of spill-over effects falls away and all coordination must be done with prices and contracts. It will be difficult to capture all spill-over costs and benefits efficiently in regulated network revenues and therefore we should expect some inefficiency to remain. More problematic may be the following issue. Above, we argued that smart contracts will have network components as well as energy components, depending on the precise details to be addressed. In an unbundled

[14] Not surprisingly, these effects are the exact opposite of the investment problem: the same incentives may cause underinvestment (i.e. withholding necessary investment).

setting, the network owner cannot charge an energy component as it is not a supplier. Therefore, the network operator would have to try to incentivize the suppliers, who in turn should incentivize the network users. While this may be possible theoretically, it is evident that it creates a governance problem.

5 Conclusion

Distributed generation and smart grids present a challenge to distribution networks. In particular the integration of renewable generation will require significant investment. In some cases network investment can be deferred by steering generation and/ or demand coordinating them with available network capacity. This coordination can be realized with institutionalized locational network or energy pricing. In systems where currently uniform pricing is in use and generators do not pay use of system charges, this would require major regulatory reform. We proposed smart contracts as an alternative tool to achieve this coordination. They can send locational signals in a low transaction cost and flexible way. Smart contracts are optional and voluntary agreements between the network operator and network customers that realize a trade-off between investment into the grid and changes at the demand or generation side.

Network operators can flexibly design these contracts to better adapt customer behavior to network capacities when this is cheaper than network investment. Since participation in smart contracts is voluntary customers are protected against exploitation by the network monopolist in the negotiations of a smart contract. They can always fall back on a regulated default tariff.

In this paper, we formally show with a numerical example that cases exist in which smart contracts can achieve a pareto-improvement. In other words, smart contracts would improve the situation for at least one party without worsening the situation for any of the others. This also illustrates how smart contracts are incentive compatible and improve overall economic efficiency.

We pick up three examples to defer network investment by using smart contracts. The first smart contract is a voluntary curtailment agreement with generators. They are compensated with the foregone revenue from curtailment plus a bonus delta to make the difference between “not-producing” and “producing”. Since this creates perverse incentives encouraging new siting at a constrained location, additional smart contracts for new generators are needed to steer them to locations with free capacity. In cases where the expenses for the diverse smart contracts exceed the expected investment cost, the network operator will expand the network which will be the efficient solution. We then also investigate smart contracts for storage and for electric vehicles inducing a locational demand shift. We find that in both cases beneficial smart contracts can be concluded without facing a problem of perverse incentives. Furthermore, storage flips between take-off and feed-in to the grid. In one period excessive production can be taken up to relieve the network. However, this energy has to be fed back at a later point in time potentially worsening the constraint and negatively affecting other network customers. In the strict sense this would violate the condition for the pareto-improvement. This might still enhance efficiency.

We conclude that smart contracts are useful as they allow a pareto-improvement in some cases (and wouldn't be used in case where the contracting parties worsen their situation). They are easy to implement and do not require large regulatory reform. Hence, smart contracts are an attractive solution for efficiency enhancing locational pricing in smart distribution networks.

We note that while pareto-improvement represents a good starting condition, this requirement might be too restrictive and leave significant potential for efficiency improvements untapped. This applies in particular since only bonus payments can be given out while negative externalities have to remain uncharged for. Furthermore, in practice the criterion will be difficult to implement if the network operator and a customer can conclude a smart contract that benefits both. They are unlikely to take all external effects into account.

Importantly, network operators need incentives to pursue smart contracts as an alternative to network expansion. This implies that they should be allowed part of the benefits from the avoided investment. It is the task of the regulator to a) allow network operators the flexibility to design smart contracts and b) to incentivize network operators such that they carry out efficient network investment and will offer smart contracts where investment can better be avoided.

Smart contracts raise further issues with regard to governance. We assume contracts can incorporate energy components. It is obvious that with unbundling this is not an easy task since network operators can only give incentives to suppliers which would than in turn design incentives for customers.

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