Bremen Energy Working Papers

JACOBS UNIVERSITY

Paperseries No. 40

Martin Palovic

Coordination of power network operators as a game-theoretical problem

October 2022

Jacobs University Bremen
Bremen Energy Research (BER)

Editors:

Prof. Dr. Gert Brunekreeft

Dr. Marius Buchmann

Jacobs University Bremen

Bremen Energy Research (BER)

Campus Ring 1 / South Hall

28759 Bremen

www.jacobs-university.de/

https://bremen-energy-research.de/

JACOBS UNIVERSITY

Contact:

Dr. Marius Buchmann

Tel. +49 (0) 421 - 200-4868

E-mail m.buchmann@jacobs-university.de

Suggested citing:
Palovic, M. (2022). Coordination of power network operators as a game-theoretical problem, *Bremen Energy Working Papers* No. 40, Jacobs University Bremen.

Coordination of power network operators as a game-theoretical problem

Martin Palovic (m.palovic@jacobs-university.de)

Bremen Energy Research; Jacobs University Bremen

Abstract

We analyse incentive problems in coordination of network operators that purchase services for electricity networks from distributed resources. Such services are often associated with externalities that make the social optimum costly against the individual one. However, a costly reaction of other operators occurs when the social optimum is missed. Regular network situations result in game-theoretical problems like prisoner's dilemma or chicken that are played in a random order in an infinitely repeated game. The outcome of this complex game-theoretical setting, i.e. adopted strategies, is difficult to predict. Adjustments to network regulation aiming to internalize external effects are discussed as a remedy.

1. Introduction

Using distributed resources to provide power grid services challenges current management of electricity networks. Services for electricity networks, i.e. network-driven adjustments to the electricity output of a facility, have been traditionally provided by bulk conventional power plants that are connected to the high voltage transmission network. This network is typically overseen by a single transmission network operator (TSO) per country who is responsible for the stability of the overall power system. Hence, TSO has been until recently the only party capable of purchasing power grid services. However, due to increase in distributed resources connected to low- and mid-voltage electricity distribution networks, such as decentralized renewable power generation, flexible power loads, small-scale power storage and power-to-X technologies, operators of distribution networks (DSO) have been encouraged to use grid services of these resources to manage distribution networks (CEER 2018; EU 2018; Ramos et. al. 2016). Distributed resources are also expected to become the dominant source of power grid services for TSO as the electricity sectors decarbonizes. Lack of coordination might easily lead in this setup to situations where grid service purchases of one network operator negatively affect other network operators. Therefore, such conflicting grid services have been recently recognized as a potential problem (EC 2020a; CEER 2020, 2016; Gerard et al 2018) and motivated significant academic work on the issue (cf. Lind et. al. 2019, Schittekatte & Meeus 2020).

Most of the current research suggests addressing the problem of conflicting grid service purchases by an improved information exchange among the operators of electricity networks (see section 2 for more details). Even though such improvements are without a doubt important and necessary, these are in our view insufficient to guarantee the cooperation of power network operators.

In this paper, we define an *incentive problem* in power network operator coordination using a game-theoretical setting. Electricity network services from distributed resources are associated with system-wide external effects. Given the external effect on other network operators in the system, the individually optimal grid service purchases of a network operator differ from the socially optimal ones, while missing the social optimum requires in reaction a potentially costly grid service purchases of other network operators. Put in a nutshell, the final grid service cost incurred by a network operator is not only dependent on the own decisions, but also on the reaction of the others. An incentive problem results that promotes strategic behaviour of the network operator.

Using a stylized power network model that is assumed to be operated by two independent network operators, we show regular network situations providing network operators with payoffs of game-theoretical problems such as prisoner's dilemma or chicken game. In fact, we show the set of possible games that emerge among the network operators to be final. Even though identifying the outcome for each game from this set becomes herewith possible, two characteristics of network operator interactions make predicting final strategies adopted by the operators of electricity networks difficult. First, the identified games are played in an infinitely repeated setting. This allows network operators adopting a wide range of reputation strategies to minimize their cost. Second, network operators do not simply play only one infinitely repeated game. Instead, the played game is selected at random from the identified games set at the beginning of each round. Such setup, i.e. an infinitely repeated setting with randomly selected stage games, does not allow defining the optimal network operator strategy by current game-theoretical tools. Herewith, the outcome of strategic network operator interactions becomes ambiguous, resp. unknown to analysts and network operators alike. Therefore, adjustments to power network regulation are discussed as a mean towards internalization of external effects within strategic network operator interactions.

In the following, section 2 defines the incentive problem in the power network operator coordination and explains how it promotes strategic behaviour on behalf of the affected operators. Using a stylized network model, section 3 shows everyday power network situations providing network operators with incentives that correspond to prisoners' dilemma (section 3.1) and chicken (section 3.2) games. Section 3.3 explains why strategic network operator interactions represent a setup where the identified games are infinitely repeated and played in a random order. Section 4 discusses the practical implications of these results and the potential counter-measures. Section 5 concludes the argument.

2. Incentive problem in the power network operator coordination

This section introduces the incentive problem in the coordination of electricity network operators. It explains why the operation of electricity networks is associated with externalities among the network operators, which give rise to incentive problems, and how such problems promote strategic behaviour on behalf of the affected network operators.

Electricity system consists of several regional medium- to low-voltage power networks, i.e. distribution networks, that are interlinked by a high-voltage transmission network. Each distribution network is managed by a separate DSO and the transmission network by a TSO. Given that electricity cannot be stored in large quantities over time, the overall supply and demand of electric power in the system is instantaneously balanced by the TSO. Furthermore, electric power flows from generation to consumption simultaneously across all lines in the system. This is portrayed in the figure 1 that presents a stylized network model used for the later analysis.

The model in figure 1 consists of two interconnected networks, i.e. of a network X and of network Y (where network X can represent other networks in a system, incl. the TSO). Nodes A, B and C are the net generators (excess production) and the node D the net consumer (excess demand). The network X is characterized by a lower line resistance R and the network Y by the line resistance of 2R per line between two nodes. Power flows in the model, i.e. the power transmission and distribution factors, are calculated in a reverse proportion to the resistance of the line. For example, when the node A generates power for the node D (the only consumer), generation from A is split on the lines AC and ABC before reaching the node C, where it proceeds over line CD to the node D. Given that the line CD is the only possible route to reach the node D, the resistance of this line does not influence the flow of power between the nodes A and C. Hence, 80% of A's generation passes through the line AC that is characterized by the resistance R, i.e. 100% x (1 – R/5R), and 20 % through the line ABC characterized by the resistance 4R, i.e. 100% x (1 – 4R/5R) towards C, as indicated in figure 1. The 20% power flow on the line B-A is marked with minus as to highlight the opposite direction flow of A's generation against the power flow indicated on the line B-A in the figure 1.

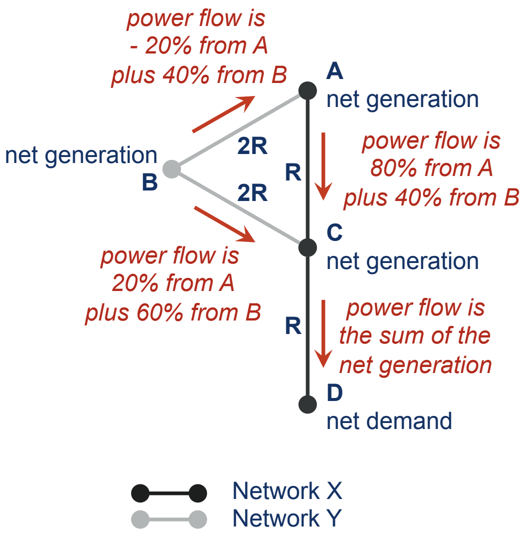

Figure 1: Stylized two-network model used for the analysis

Figure 1 includes power transmission and distribution factors resulting from such calculations for all generators in the model. As implied by this figure, power gird service purchase at, i.e. an output adjustment to, the node A in network X affects the power flows of the network Y in addition to the those in network X. Similarly, an adjustment of output at the node B in the network Y affects power flows on the lines of both the X and Y network. Put differently, grid service provision at both nodes is associated with an external effect on other network. As opposed to this, node C in the network X affects congestion only on the line CD in the network X. Nevertheless, adjustments to output at any of the three nodes, i.e. including the node C, affect the system-wide balance between the overall demand and supply. Hence, grid service purchases at any node might require TSO involvement if not properly accounted for by the grid service purchasing DSO.

Put in a nutshell, power grid service purchase of a given network operator, i.e. an output adjustment of a certain power generation or load facility, tends to affect the power flows and the supply-demand balance of the overall system and herewith the electricity networks and power grid service purchase needs of other network operators. Electricity network operators have understood this setup as an *information problem* and have been primarily concerned about the insufficient information with respect to the effect of their power grid service purchases on the electricity networks of other network operators and on the grid service demand in these networks (cf. CEDEC et. al. 2019). Correspondingly, most of the current academic and practical discussion focused on the information problems among the network operators and provided several different models improving the coordination of grid service purchases among these (Gerard et al. 2018; ECOFYS & IWES 2017; ENA 2017). By now, the short-term efficiency (Papavasiliou & Mezghani 2018), social and policy requirements (Rossi et. al. 2020) and acceptance among the relevant stakeholders (Neuhoff et al. 2018; Neuhoff & Richstein

2017) for these models have been understood. Clearly defined roles for the TSO and DSOs, transparent network operation, planning and information exchange on the external effects of the activated grid services are few examples of the resulting remedies. The follow-up works on the information problem highlight the difficulties associated with the implementation of these remedies, such as technically extending the current single TSO or DSO network optimization models as to include other network levels (cf. Dzikowsko 2020, Edmunds et. al. 2020, Yuan & Hesamzadeh 2017) or the limited knowledge on the system-wide impact of grid services from decentralized resources (Grøttum et. al. 2019).

However, solving the information problem, even though important and necessary, is insufficient when a power system managed by several network operators should reach the social optimum. Electricity networks are characterized by externalities that occur between the operators of electricity networks, as explained above. Such externalities are likely to promote *incentive problems*, i.e. situations where the individual incentives of the power network operator might deviate from the social optimum.

In the case of negative externalities, the network operator does not consider the negative effect of the gird service on the other parts of the system. The price observed by the network operator is hence lower than the social price. When the power network operator has an incentive to minimize the cost, as common in the current regulation of electricity networks (Joskow 2005), the network operator tends to contract more grid service from the provider than would be socially optimal. As opposed to this, the network operator does not consider the positive effect of the grid service on the rest of the electricity network in case of positive externality. The price of the gird service observed by the network operator is hence higher than the social price that considers the benefits of the grid service provider in the other parts of the network. In result, a cost-minimizing network operator tends to contract less grid service from a given source than would be socially optimal. Put in a nutshell, adjusting the grid service purchases in order to account for the externality is likely to be costly for the power network operator, as this implies a deviation from the individual optimum. Expecting any deviation from the individual optimum to be irrational, an incentive to deviate from the social optimum exists.

However, aware of the external power network effects explained above, any deviation from the social optimum by one network operator leads to potentially costly deviations from the social optimum by other network operators. To see the point, one might consider the example of congestion management presented in figure 2. If one network operator (NO1) due to cost savings contracts less power grid services from a distributed resource than would be socially optimal, external effects might result in a change of electricity flows that drive another network operator (NO2) to contract more power grid services from another source somewhere in the same network area. This reaction of NO2 might again change the electricity flows in the network of NO1 to a degree, where NO1 needs to contract additional power grid services. The cost of the additional grid services contracted by the NO1 might reduce or even increase the savings achieved by deviating from the social optimum at the first place.

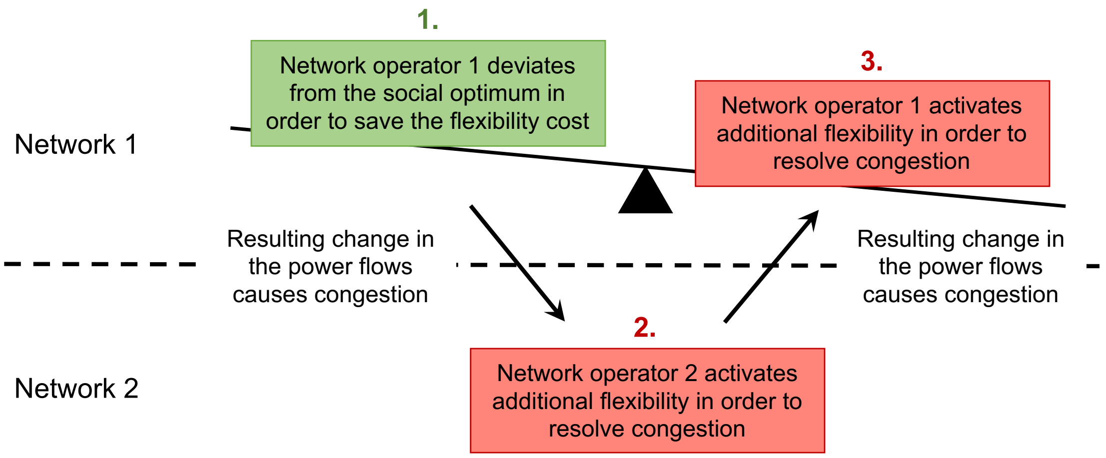

Figure 2: Strategic interactions of network operators within congestion management

Hence, the cost of the power grid service can be assumed to be dependent not only on the own decisions of the given network operator, but also on the decisions of the other network operators. A system where stakeholders can influence the costs of each other are conductive to strategic interactions. Put more explicitly, rational well-informed network operators have an incentive to behave strategically in order to minimize the individual cost of the grid services.

Strategic character of interactions among the operators of electricity networks has been observed previously by Glachant and Pignon (2005) as well as Bjørndal and colleagues (2003) at the international Nordic power market. This provides TSOs managing the national networks of the participating countries with two different congestion management mechanisms to address congestion that occurs within and across the national borders. The authors show the observed setup to provide a rational TSO with an incentive to select the mechanism associated with a lower individual cost even if this causes additional cost to TSO managing other network area in the market. Vicente-Pastor and colleagues (2019) suggest similar incentive problems to occur in the TSO-DSO cooperation. Unfortunately, the authors do not provide a more detailed analysis of the problem. Probably the most detailed analysis of strategic interactions among the operators of electricity networks was provided recently by Le Cadre and colleagues (2019). They study the behavior of transmission and distribution network operators that sequentially, i.e. one after another, acquire balancing services from the distributed resources. In one scenario, bounded rationality of network operator is additionally assumed. The study finds sequential optimization of the power network to be in particular prone to strategic behavior of the network operators. Social efficiency losses occur in result. Bounded rationality on the part of the network operators is found to be associated with a similar effect but of a lower magnitude.

However, as shown in the analysis below, externalities might promote strategic behavior even among fully rational, well-informed network operators that simultaneously optimize the network. This is the result of game-theoretical problems that emerge from the payoffs of network operator interactions.

3. Strategic interactions promoted by incentive problem

In this section, we define the interactions of network operators as a game-theoretical problem. Using the stylized network model presented in figure 1, Section 3.1 and 3.2 show everyday power network situations to provide network operators with incentives that correspond to the well-known prisoners' dilemma and chicken games respectively. Analytical fundamentals, which allow us to formulate the numerical setup in these sections, can be found in the appendix. Based on these results and further characteristics of network operator interactions, section 3.3 defines power network operator interactions as an infinitely repeated setting where prisoner's dilemma and chicken games are played in a random order.

In the analysis below, provision of power grid services for the purposes of network congestion management is evaluated. In line with a common power market practice in many European countries, we assume a stylized electricity system where power market clearing does not consider network constrains. These are addressed in a separate re-dispatch stage that follows the market clearing. Every electricity network in the model is operated by a different network operator that carries the cost of grid services purchased to manage the respective network. Furthermore, the cost of the system imbalances, i.e. changes in the balance between the overall demand and supply in a system due to grid service purchases, is allocated at the network operator that purchases the service. We build our analysis on the ideal conditions for the cooperation of the network operators that are defined in the current literature (Oggioni & Smeers 2013): Every network operator has perfect information on the complete network topology (i.e. the whole system) as well as an unconstrained access to all flexibility providers located in a system. Given this setup, every network operator can perfectly predict the reaction of the other network operator and account for it in his decisions. Grid services are purchased by both network operators simultaneously.

3.1 Network situation leading to prisoner's dilemma

Below, we introduce a network setup as this might emerge from the clearing of the power market. The analysis of this setup shows that the resulting grid service needs and price offers result in a cost structure that places studied network operators into a prisoner's dilemma game.

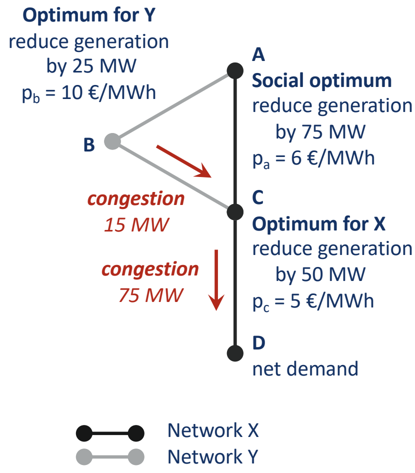

Figure 3: Strategic network interaction conductive to prisoner's dilemma game.

Network situation depicted in figure 3 triggers strategic interactions between the network X and Y. Congestion of 15 MW on the line BC as well as congestion of 75 MW on the line CD have been observed in the system after the power market has cleared. The net cost of flexibility indicated for each node in the figure 3a reflects the difference between the income of a network operator from reducing the output at the given net generation node and the cost from balancing this output loss at the net consumption node D. The socially optimal solution is to reduce the output of the node A by 75 MW, that is located in the network X. Corresponding to the figure 1 and the associated calculation introduced in section 2, this output reduction of A reduces congestion at the line BC by 15 MW, i.e. by 20% of A's generation reduction, and at the line CD by 75 MW, i.e. by 100% of A's generation reduction. Congestion in both networks is resolved in result. The total cost of congestion management is 450 EUR (75MW * 6€/MWh).

However, will the socially optimal solution be realized by two independently acting rational network operators? There are in principle two different strategies that allow the network operators to account for the external effects between the two studied networks. A network operator might decide to cooperate in order to utilize the synergies provided by the externalities. The socially optimal solution results. Alternatively, a network operator might decide to free-ride, i.e. use the external grid service effects to reduce the own share on the total grid service costs. If successful, this strategy allows to shift the cost of grid service at the other network operator in the system. Importantly, a rational network operator will decide on the two strategies based on their expected payoffs. These in turn are dependent on the specific network situation.

Hence, any network situation, where an acquisition of a grid service is associated with an externality, can be represented as a game theoretical problem. Network operators affected by the grid service should be assumed to be rational cost-minimizing players of the given game. Each of the network operators decides between the strategy of free-riding and cooperating with others. The individual payoff, i.e. the share of the respective network operator on the total cost of the grid service, is dependent not only on the selected strategy, but also on the strategy selected by the other network operators in the game. In result, network situation presented in figure 4 leads to four possible sets of pay-offs for the networks X and Y, namely

1. both networks defeat,
2. both networks cooperate,
3. the network Y cooperates, the network X defeats and
4. the network X cooperates, the network Y defeats.

How to define the sets of payoffs for the network situation presented in the figure 3a?

First, define the payoffs of the network operators for a setup where both defeat (scenario 1). Since both network operators have full information, they anticipate the congestion measures of each other. Network operator Y anticipates that network operator X will opt for the output reduction at the node C, since this measure resolves the congestion in the network X at the lowest cost. At the same time, adjusting the output of C has no impact on the congestion between the nodes B and C, which Y is responsible for. Therefore, network operator Y has to address the congestion on the line BC on his own. Reducing power by 25 MW at node B represents the cheapest solution for Y; power reduction by 75 MW at node A, which also resolves congestion at the line BC, is more expensive (see figure 1). Hence, network operator Y incurs the cost of 250 EUR in result. Congestion management measures of the network operator Y reduce the congestion on the line CD by 25 MW (see figure 1). Anticipating the congestion management of Y, it is sufficient for the network operator X to reduce the output of the node C by 50 MW. This minimizes the congestion management cost of X, which equals to 250 EUR.

Turning to scenario 2, it is not possible to precisely predict the split of the congestion management cost between the two network operators without an additional information on the broader framework of the game, i.e. on the respective negotiating power of the two network operators. However, given the synergies from activating the socially optimal grid service from the node A, the payoff of each network operator from cooperation would be typically expected for a single-round game to stay below the cost of the individual optimum for each network operator, which was shown to be 250 EUR. For simplicity purposes, let us therefore assume that the two network operators agree to reduce the power output of node A by 37,5 MW each when cooperating. The cost of A, i.e. 450 EUR, is in such a case split equally between the two (225 EUR).

With this information, the payoffs for the scenario 3 and 4 can be defined. We perform a thought experiment for this purpose. We assume that the network Y cooperates and, at the same time, addresses congestion in his network due to defeat of X. What is the cost-minimal solution for Y? When cooperating, network Y reduces the output of the node A by 37,5 MW. Herewith, congestion at the line BC will get reduced by 7,5 MW (see figure 1). If network X defeats, it opts for the cheaper output reduction of the node C instead of activating flexibility at the node A. Given that output of C has no effect on the BC line, Y needs to resolve the remaining congestion on this line himself. Y minimizes the cost by contracting additional power reduction from the node B instead of A. Therefore, Y will reduce the output of node B by 12,5 MW in addition to his obligations stemming from the cooperation. Herewith, congestion between nodes B and C will be resolved even if the network X defeats. The cost incurred by Y is 350 EUR. If X anticipates this behaviour of Y, reduction of congestion on CD line by 50 MW can be foreseen (see figure 1). Herewith, it is sufficient for X to reduce the power output at node C by 25 MW in order to resolve the remaining congestion. Hence, the cost of X is 125 EUR.

On a similar note, network X expects the network Y to reduce the output of node B by 12,5 MW in case of defeat, as this minimizes the cost of Y (125 EUR) when X cooperates. Therefore, in addition to output reduction on the node A by 37,5 MW, network X needs to reduce the output at the node C by 25 MW in order to resolve congestion remaining at the line CD. Herewith, X incurs an additional cost equal to 125 EUR in addition to the 225 EUR stemming from the cooperative behaviour.

Prisoner's Dilemma Game		**Network X**	
		Cooperate	Defeat
Network Y	Cooperate	*37,5 MW from A* **225 €** *37,5 MW from A* **225 €**	*25 MW from C* **125 €** *37,5 MW from A 12,5 MW from B* **350 €**
	Defeat	*37,5 MW from A 25 MW from C* **350 €** *12,5 MW from B* **125 €**	*50 MW from C* **250 €** *25 MW from B* **250 €**

1.

Figure 4: Gird service costs of the network operator X (top-right) and Y (bottom-left) for the available purchasing strategies result in prisoner's dilemma game.

Figure 4 summarizes the payoff sets for the networks X and Y in the four studied scenarios. The resulting pay-off matrix is typical for the prisoner's dilemma game. Each of the two network operators is confronted with a dominant strategy towards the non-cooperative behaviour. Therefore, a non-cooperative outcome, which is socially inefficient, should result for a single-round game.

3.2 Network situation leading to chicken game

In this section, we study an almost identical market clearing result to the setup studied in the section 3.1 (cf. figure 5). The only difference is a lower price bid for grid services at the node A. Below, we show the model after this small adjustment to provide the studied network operators with a payoff-structure of chicken game.

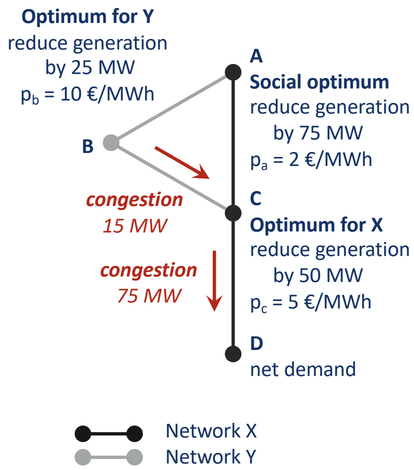

Figure 5: Strategic network interaction conductive to chicken game

As shown in figure 5, the price of grid service on the node A was reduced from 6 EUR per MWh down to 2 EUR per MWh. Herewith, the cost of the social optimum is identical to the individual optimum of both networks. More specifically, reducing the output of node A by 75 MW is associated with a lower cost (75MW * 2€/MWh = 150EUR) than resolving the congestion in the network Y by reducing the output of B by 25 MW (25MW * 10€/MWh = 250EUR) and addressing the congestion in the network X by reducing the output of C by 50 MW (50MW * 5€/MWh = 250EUR).

How does this light modification of the model change the pay-off sets for the four scenarios?

In deriving the pay-off matrix of this setup, we skip the scenario 1 set of pay-offs for a moment. We move directly on the scenario 2 instead. Lacking again information on the negotiating power of the two network operators, we assume both network operators to cooperate by splitting the required flexibility equally and reducing the power on the node A by 37,5 MW each as in the analysis above. The cost of cooperation is equal to 75 EUR for every network operator, which is lower than the cost of the individual optimum equal to 150 EUR. Hence, both network operators can benefit from cooperation. Pay-off sets for the third and the fourth scenario can be derived by the same thought experiment as in the analysis of the figure 3a. As discussed in the paragraph above, every network operator will find reducing generation at node A by additional 37,5 MW to represent the lowest cost solution, if the other party defects. Therefore, defecting network operator can free-ride on the congestion management of the other network operator, if the cooperative behaviour of the counterpart is correctly predicted.

Lastly, what are the pay-offs of the defeat-defeat scenario (scenario 1)? There are two potential solutions for the non-cooperative outcome. First, damage to the congested line might occur if both network operators attempt to free-ride and undertake no adjustment of generation. This would be extremely costly compared to activating the flexibility at any node in the system. Therefore, some kind of last-resort solution that adjusts the power flows, such as controlled blackout, is likely to occur. Even though less costly than damage to the lines, the costs of an emergency solution should be considered high as these are likely to be followed by a regulatory investigation and a threat of penalties. Second, network operators might intentionally opt for the flexibility at the nodes B and C in order to defeat. This behaviour is rational when every network operator in the game expects a defecting counterpart but wishes nevertheless signalling a non-cooperative behaviour, e.g. in order to maintain a non-cooperative reputation for later games with other network operators. Herewith, a regulatory action can be avoided even if all network operators defect. The cost of such non-cooperative outcome is 250 EUR for each network operator in the studied example.

Chicken Game		**Network X**	
		Cooperate	Defeat
Network Y	Cooperate	*37,5 MW from A* **75 €** *37,5 MW from A* **75 €**	*0 MW from A* **0 €** *37,5 MW from A* *37,5 MW from A* **150 €**
	Defeat	*37,5 MW from A* *37,5 MW from A* **150 €** *0 MW from A* **0 €**	*emergency or* *50 MW from C* **250 €** *emergency or* *25 MW from B* **250 €**

Figure 6: Gird service costs of the network operator X (top-right) and Y (bottom-left) for the available purchasing strategies result in chicken game.

Figure 6 summarizes the above analysis in a pay-off matrix. In game theory, the chicken game is typically presented by this type of a pay-off matrix. The outcome of a single-round chicken game cannot be predicted. As opposed to a pay-off matrix presented in the figure 4, network operators cannot maximize their payoffs by following a certain dominant strategy within the figure 6. Instead, it is better to defeat when the other party cooperates and vice versa. Unfortunately, neither the analyst, nor the network operators, can predict who cooperates and who defeats. In result, any of the four outcomes can occur without additional coordination mechanisms.

3.3 Network operator interactions as an infinitely repeated setting with randomly

selected stage game

Given the results of the analysis above, the game-theoretical problem played by the operators of electricity networks can be defined. This is done by considering the identified games in the framework of common network operator interactions.

Network operators have been shown in the previous analysis to face prisoners' dilemma and chicken games when interacting with respect to grid service purchases. In fact, as shown in the appendix, the set of games that a network operator might face when interacting with others is final. When plaid only once in a static setting, as above, the outcome of each game from this set can be predicted. However, two characteristics of network operator interactions make predicting the final strategies adopted by the operators of electricity networks difficult.

First, one should consider that network operators interact with each other frequently and on a regular basis when purchasing grid services from the distributed resources. Depending on congestion level in the network, network operators might interact with each other due to several different network constraints and even several times per day and constraint. An entry of an additional network operator into such interactions due to newly emerging network constraints, or an exit of established players due to network expanding investment are rather rare in comparison to the overall number of existing interactions.

Hence, the above-specified non-cooperative games occurring in the interactions of network operators should not be considered as static one-shot games. Instead, these can reasonably be assumed to be characterized by a repeated infinite setting, resp. a setup where the played game has a very low probability of becoming the last one. Such a repeated setting provides space for a wide range of reputational strategies that might be applied by the network operators in order to minimize the cost. This point alone makes predicting the outcome of network operator interactions difficult. However, it is not impossible. Games like prisoner's dilemma and chicken have been extensively studied for infinitely repeated setting. Furthermore, game theory provides established tools that allow solving also other games in an infinitely repeated setting (cf. Carroll 2020).

Second, observation made in the section 3.2 further complicates the matters. Section 3.2 showed that already a small change to specifications of the network situation, i.e. a different price-bid of a grid service provider, can change the pay-off structure of the affected network operators to a different game-theoretical problem. Put differently, the specific game-theoretical problem faced by the interacting power network operators seems to be highly sensitive to the available grid-service bids, assumed network topology and the current power flows. Prices of grid services or power flows resulting from market clearing change in practice frequently as these are dependent on the temporal availability of generation and loads and herewith on external factors such as demand availability or even weather (consider renewable generation).

Hence, the game-theoretical problem faced by the network operators is not only characterized by an infinitely repeated setting, but also by changing stage games, i.e. by a setup where the played game is selected randomly and changes possibly as frequently as every 15-minutes per day. Optimal network operator strategy cannot be defined for such setting using current game-theoretical tools. The established game-theoretical methods were developed for a repeated setting with a single stage game. Methods capable of solving an infinitely repeated game with several different stage games that are played in a random order are subject to the ongoing research (Carroll 2020). In result, the outcome of strategic network operator interactions is ambiguous, resp. the optimal strategies are unknown to analysts and network operators alike.

Summing up, section 3 has shown that regular network situations might provide network operators with pay-off structures that remind of non-cooperative games such as prisoner's dilemma or chicken game. Even though the set of possible games that emerge among the operators of electricity networks is final, these games are played in an infinitely repeated setting in a random order. Herewith, rational network operators have an opportunity to minimize their costs by developing a wide range of reputational strategies. Importantly, strategies adopted by the network operators in this setting cannot be predicted using established game-theoretical tools, resp. are unknown to the analysts and network operators alike. Herewith, the final outcome of the identified game-theoretical problem is ambiguous and the optimization of the network by grid service purchases of different network operators is not guaranteed. This makes a policy action necessary.

4. Implications and remedies

What are the practical implications of the above defined game-theoretical coordination problem in the power network operator interactions?

One should expect the current trend towards grid service provision from the distributed resources and their more frequent use by DSOs to lead to a significant increase in incentive-driven coordination problems among the network operators. Herewith, the risk of missing the social optimum, i.e. some networks minimizing their grid-service expenditures at the cost of others, increases. This represents a problem as network operators use the cost of power grid services to identify the network expansion needs. Hence, redistribution of costs among the network operators not only increases overall grid service expenditures in the short run but also displaces new network investments that are intended to substitute the grid service purchases. Similarly, end-user network charges, which are defined by the cost of a respective network operator, might de-couple from the true network cost and provide perverse incentives for the location of new power generation and consumption facilities. Both effects are difficult to identify and make the power system inefficient in the long run.

Fortunately, significant attention has been given recently to problems associated with the optimization of the energy system as a whole (cf. EC 2020a). The need to improve coordination among the operators of electricity networks is a part of this ongoing discussion.

Power transmission network has been traditionally developed by a common planning of the TSOs. In order to account for the new developments in the electricity sector, i.e. increasing shares of distributed resources and the increasing role of the DSOs, the idea is to include the DSOs into the established planning processes. The resulting improvement in information exchange among the TSOs and DSOs should promote the cooperative development of the electricity networks and hence the efficiency of the system (cf. EC 2020b).

Considering the above findings on incentive problems, one should be critical of this approach and of the underlying assumption on the cooperative behavior of network operators. It is unclear how improved information exchange alters the potential incentive misalignments among the network operators. Network operators, i.e. TSOs and DSOs, faced with the above-identified game-theoretical problem might find it of an advantage to behave strategically, resp. to strategically communicate, when participating in the common planning processes.

Promoting the whole system optimization by regulatory measures, i.e. extending the current energy network regulation by additional outputs next to the individual cost minimization, might represent a remedy (cf. Brunekreeft et. al. 2020). This solution implies in game-theoretical terms altering the network operator payoffs as to promote cooperative behavior.

The most straight-forward option in this context is internalizing external network effects of grid services. However, one should keep in mind that the above defined game-theoretical problem cannot be properly analyzed and predicted with the current game-theoretical tools. This might turn proper internalization of external effects difficult. In such a case, one might alternatively focus on similarities in the payoffs of prisoner’s dilemma and chicken games that characterize network operator interactions. The only difference between the two games is the preference of a prisoner’s dilemma player to defeat when confronted with a non-cooperative behavior, whereas cooperative behavior is chosen in a chicken game (see appendix). Hence, the game-theoretical problem identified in the section 3.3 can be converted ‘only’ into an infinitely repeated prisoner’s dilemma game by providing every network operator with an incentive to behave non-cooperatively when non-cooperative behavior of other network operators is observed. Naturally, the resulting problem, i.e. endlessly repeated prisoner’s dilemma, is still complex. As opposed to the current setting, it can be analyzed and addressed by the established tools of the game theory.

5. Conclusion

In this paper, we evaluate incentives of power network operators to optimize the electricity network as a one system. Such optimization is for example needed between transmission network operators or between the transmission and distribution network operators. We argue that increasing use of distributed resources, such as decentralized renewable generation, storage or flexible loads, for grid service purposes leads to coordination problems consisting of non-cooperative games like prisoner's dilemma and chicken game.

Due to their location in distribution networks, grid services of distributed resources, i.e. their network-driven output adjustments, tend to affect power flows and the supply-demand balance in the overall power system. Put differently, grid service purchases of a given network operator influence different network levels and network regions simultaneously. Given that the different network levels and regions are typically managed by different network operators, externalities among network operators occur. Herewith, the individually optimal grid service purchases of a network operator differ from the socially optimal ones. At the same time, missing the social optimum requires in reaction a potentially costly grid service purchases of other network operators. Put in a nutshell, the final grid service cost incurred by a network operator is not only dependent on the own decisions, but also on the reaction of the others. In result, an *incentive problem* occurs where rational well-informed network operators should be expected to behave strategically to minimize their individual cost of grid services.

There are two different strategies that can be followed. Network operator can either cooperate in order to utilize the synergies provided by the external effects or defeat in order to shift the grid service cost at the other network operators in the system with the help of the external effects. The most rewarding strategy is expected to be selected by a rational cost-minimizing network operator. In the analysis, we show regular network situations to lead to payoffs of game-theoretical problems such as prisoner's dilemma or chicken games. In fact, network operators are suggested to face only a final set of games when interacting with others. Herewith, strategies adopted by the network operators can be predicted for each of these games.

However, two characteristics of network operator interactions complicate the matters. First, network operators interact with each other frequently when purchasing grid services, i.e. an entry of a new or an exit of an established players are very rare in comparison. Therefore, the identified games should be assumed to be played in an infinitely repeated setting. This allows network operators adopting a wide range of reputation strategies minimizing their cost. Second, already a small change in network setup, such as a new grid-service price-bid, has been shown to change the pay-off structure of the affected network operators to a different game-theoretical problem. Put differently, game played by the interacting power network operators seems to be highly sensitive to the available grid-service bids, assumed network topology and power flows. These are dependent on the network user availability and are likely to change frequently. Herewith, network operators do not simply play only one infinitely repeated game. Instead, the played game is selected at random from the identified games set at the beginning of each round.

In result, network operator interactions are presented as a game-theoretical problem with a final set of stage games where the played game is selected from a pre-defined set at random and has a very low probability of becoming the last one. Simply put, the game-theoretical problem faced by the network operators is not only characterized by an infinitely repeated setting, but also by randomly changing stage game. Methods capable of solving this type of game-theoretical problems are subject to the ongoing research (Carroll 2020). This makes the outcome of strategic network operator interactions ambiguous, resp. does not allow predicting the optimal strategies. Hence, the optimization of network cannot be guaranteed without further policy action. Adjustments to network regulation are discussed as a potential remedy. Introducing additional outputs next to the individual cost minimization can in this context alter the network operator payoffs as to promote cooperative behavior.

Acknowledgments

This study was supported by Federal Ministry of Education and Research (BMBF grant no. 03EK3055B D.W.). The author would like to thank to Gert Brunekreeft and Marius Buchmann as well as to participants of Zukünftige Stromnetze 2020 conference and to participants of various workshops within CoNDyNet and enera projects for their helpful comments on the works preceding this publication.

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Appendix: Definition of the stage games set in power network operator interactions

In this appendix, we suggest any strategic interaction among the operators of electricity networks to always result in a final set of payoff-matrixes, i.e. stage games. Section A.1 identifies the structural similarities in the interactions of power network operators along two dimensions. Herewith, four model interactions are defined. Section A.2 studies the payoff structure of these four model interactions and finds two of these to correspond to prisoner's dilemma game. Payoff structure in one of the model interactions corresponds to chicken game. The last model interaction is found to represent a completely different game, where a group of power network operators faces payoffs promoting a dominant strategy while another group is incentivized to do the opposite of their counter-players.

A.1 Structural similarities in interactions of network operators

In this section, we show all potential network operator interactions to correspond to only four model types. These differ from each other along two dimensions. The first dimension is the relative cost of the socially optimal grid service provider against the cost of the grid service provider that represents the individual optimum of the network operator. The second dimension is defined by the external effect that is associated with the socially optimal grid service provider.

In the following, we define grid service provider that resolves the problem in the system at the lowest cost as the social optimum (SO). Given the cost-minimizing incentive of the network operators discussed in section 3.1, every network operator *n* is assumed to activate grid service provider that address the own network problems at the minimum cost instead of searching for the SO, i.e. the individual optimum for this operator (IO_n). When focusing on the structural similarities in the network operator interactions, there are three possibilities on how the cost of the SO can relate to the cost of the IO_n, namely

1) SO cost corresponds to the cost of the IO_n of every network operator in the system, i.e. SO represents the individual optimal choice for every network operator in the system (this would be the case when the SO is the cheapest grid service bid),
2) SO cost corresponds to the IO_n cost of some network operators in the system while exceeding the IO_n cost of the other network operators, or
3) SO cost exceeds the IO_n cost in case of all network operators but it is lower than the cost incurred by at least one arbitrarily selected group of network operators relying on their individual IO_ns.

Note that any other possibilities are unavailable. The definition of SO implies that the SO has to always be beneficial for at least one arbitrarily selected group of the network operators in the system when compared to the sum of their IO_n costs. Furthermore, the definition of IO_n implies that the cost of the SO can never be lower than the cost of the IO_n.

Another structural similarity in the network operator interactions is the external effect of the SO[1]. Its externality can be either

1) positive, i.e. decrease the stress in the networks of the affected network operators, resp. reduce their management cost, or
2) negative in the sense that it increases the stress level of the affected networks, resp. the cost of their management.

Based on this generalization, six categories of network operator interactions emerge, as shown in the table 1. However, closer examination reveals only four of the six categories as feasible. Category 1N describes a situation where the SO corresponds to the IO_n of every network operator and, at the same time, has a negative external effect. Note that such combination is per definition not possible as the SO cannot represent an IO_n for a network where it has a negative effect. Similarly, the category 3N is also not feasible. It represents a situation where the cost of SO exceeds the cost of IO_n, i.e. represents a sub-optimal choice, for any network operator, while activation of the SO benefits these network operators as a group through its negative externality. If the SO is associated with a negative externality and does not correspond to IO_n of at least one network operator, then there is no positive effect that would compensate its negative externality. Hence, a given grid service provider cannot be the SO.

Under these considerations, all potential network operator interactions related to grid service management can be summarized by four model interactions presented in the table 1 below.

	Cost of flexibility	External effect of SO	
		Positive	Negative

[1] If the SO is associated with no external effect, no interaction among the network operators occurs.

1)	SO = IO_n	**Model interaction 1P**	**Model interaction 1N** not feasible
2)	SO = IO_A > IO_B	**Model interaction 2P**	**Model interaction 2N**
3)	SO > IO_A SO > IO_B SO < IO_A + IO_B	**Model interaction 3P**	**Model interaction 3N** not feasible
SO – social optimum IO_n – individual optimum of n n – n^{th} network operator in the studied system A – an arbitrary group consisting of at least one network operator that belongs to n B – an arbitrary group consisting of at least one network operators that belongs to n so that A ∈ n – B			

Table 1: Model network operator interactions

A.2 Game-theoretical problems in the model network operator interactions

By studying the payoffs of the two network operator strategies defined in the section 3.1 within each of the four model interactions, game-theoretical problems within the network operator coordination can be defined.

Activation of SO represents the IO_n for every network operator in the model interaction 1P. Furthermore, SO is associated with a positive externality. The preferences of all network operators can be assumed to be the same. Activation of the SO, i.e. cooperating (C), is the best response to defeat (D) in the model interaction 1P. Hence, defeating while the others cooperate (DC) represents the best possible outcome for every cost-minimizing network operator. Herewith, the freeriding network operator benefits from the grid service while the cost is carried by others. The worst outcome occurs when the SO is not activated, i.e. if all network operators defeat (DD) and try to free-ride. Outcome penalized by authorities or even system damage occur. Given the possible DD outcome, cost-minimizing network operator prefers to activate the SO even if the other network operators defeat (CD). Such an action is rational as the activation of the SO implies activating the IO_n for every network operator. Clearly, splitting the SO cost with others, i.e. cooperating while others cooperate (CC), is less attractive than the DC outcome but preferred to the CD outcome. The resulting pay-off structure from the model interaction 1P can be summarized as DC > CC > CD > DD. This payoff structure is typical for the chicken game.

Model interaction 3P represents a situation where the SO cost exceeds the cost of IO_n for every network operator but is lower than their sum. As specified above, SO has to be associated with a positive externality for this model interaction to be feasible. All network operators can be again assumed to have identical preferences. Due to its positive externality, every network operator benefits from the synergies provided by the SO. However, IO_n represents individually the better choice. Hence, the best outcome for every network operator is again to defeat while the others cooperate and carry the cost (DC). As opposed to model interaction 1P, the worst outcome for a network operator is to cooperate while the others defeat (CD). Herewith, the cost of the IO_n is exceeded. Defeating when other defeat (DD) will be preferred to the CD outcome. Cooperating while others cooperate (CC) allows to benefit from the synergies of the SO and to reduce the cost of the grid service below the IO_n. Herewith, the CC outcome is less attractive than the DC outcome, but more attractive than the DD outcome. In result, model interaction 3P provides every network operator with the payoffs DC > CC > DD > CD, which are typical of the prisoner's dilemma game.

Network operator preferences from the model interactions 1P and 3P can be used to define preferences of network operators in the model interaction 2P. 2P describes a setup where the SO is associated with a positive externality. The cost of SO corresponds to IO_n for a group of network operators called *A*. Corresponding to model interaction 1P, the preferences of this group can be defined as DC > CC > CD > DD. For the other group of the network operators called *B*, SO is more costly than the IO_n. However, given that SO represents the social optimum for the group A, the contribution required from the network operators in the group B can be assumed to be lower than the sum of their IO_ns, if cooperation takes place. Put differently, the preferences of the network operators in the group B can be said to correspond to the preferences of the network operators from the model interaction 3P, i.e. DC > CC > DD > CD. In result, preferences of the network operator n within the model interaction 2P are defined by the relative cost of the SO to the IO_n. Herewith, the model interaction 2P introduces a new games with payoff elements known from chicken and prisoner's dilemma games.

Model interaction 2N assumes a network operator[2] that activates SO with a negative externality. In line with the current practice (cf. entso-e 2018), network operators are assumed to have a right to restrict the use of a grid service by others if negatively affected by it. Therefore, network operator n has not only to carry the cost of the SO, but also to compensate the negatively affected network operators in order to avoid restrictions on the SO.

Turning to such a network operator first, the best possible outcome would be to activate the SO without compensating the negatively affected network operators, i.e. to defeat while the others cooperate (DC). The worst outcome would be to compensate while the use of the SO is restricted, i.e. cooperating while the others defeat (CD). Clearly, if the use of SO is restricted,

[2] A network operator activating the SO can also represent a group of network operators. In such a case, the given strategic interaction should be modelled as two separate model interactions. First, the group of network operators activating the SO is studied according to model interactions 1P to 3P. These network operators are presented as a single network operator within the model interaction 2N.

network operator has to active an alternative and more costly provider of a grid service (DD). As this outcome foregoes the benefits of activating the SO, cooperating while the other cooperate (CC) and compensating the negative SO effects has to be less costly than switching to an alternative grid service provider. The payoff structure of the SO activating network operator is hence DC > CC > DD > CD.

Taking the perspective of a negatively affected network operator, restricting the SO while getting compensated is the most optimal outcome (DC). The worst outcome would be to carry the cost of the negative externality while receiving no compensation payment (CD). Restricting the use of the SO, i.e. forcing the activating network operator to use an alternative grid service provider (DD) allows to avoid negative external effects and hence is preferred to DC outcome. As this outcome is sub-optimal, compensation payment that is higher than the cost of the SO externality can be achieved, if cooperating with the network operator that activates the SO (CC). In result, the model interaction 2N provides negatively affected network operators with a pay-off structure that corresponds to the one of the activating network operator. Prisoner's dilemma game emerges in result.

Table 2 provides an overview of the game-theoretical problems that are associated with the model network operator interactions identified in the section A.1. These are the well-known non-cooperative games chicken and prisoner's dilemma games and an additional game that combines pay-off elements of the two games.

	Cost of flexibility	External effect of SO	
		Positive	Negative
1)	SO = IO_n	**Model interaction 1P** Payoff structure DC > CC > CD > DD ∈ n (Chicken)	**Model interaction 1N** not possible
2)	SO = IO_A > IO_B	**Model interaction 2P** Payoff structure DC > CC > CD > DD ∈ A DC > CC > DD > CD ∈ B	**Model interaction 2N** Payoff structure DC > CC > DD > CD ∈ n (Prisoner's Dilemma)
3)	SO > IO_A SO > IO_B SO < IO_A + IO_B	**Model interaction 3P** Payoff structure DC > CC > DD > CD ∈ B (Prisoner's Dilemma)	**Model interaction 3N** not possible
SO – social optimum	IO_n – individual optimum of n	D – deceive	C – cooperate

n – n^{th} network operator in the studied system A – an arbitrary group consisting of at least one network operator that belongs to n B – an arbitrary group consisting of at least one network operators that belongs to n so that $A \in n - B$

Table 2: Overview of game-theoretical problems in the model network operator interactions