Title of the proposal:	*Game-theoretic modelling and mechanism design of energetic networks and systems*
Principal investigator:	Dávid Csercsik
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Final report

1 Introduction

1.1 Motivation and context

Energetic infrastructure networks, which ideally provide access to clean and affordable energy, are cornerstones of modern societies. Due to their serious economical impact, these systems have prominent significance on the level of governmental strategy as well. In the global, as well as in the regional energy economics, states, wholesale energy providers, traders, operators, regulators, and other actors with conflicting interests are interacting in various markets and time scales. The underlying physical and technological considerations make these energy markets – especially electricity and electricity-related markets [13] – quite special and challenging. The unique nature of these markets often requires a multidisciplinary approach to properly address the arising problems and to make the optimal utilization of the installed infrastructure possible: Engineering and economical aspects often play equally important roles in these highly interconnected systems. In addition, the evolution of economic theory also offers novel tools for the analysis and design of such markets. Cooperative game theory [4, 2] and mechanism design [1] represent relatively novel branches of economical mathematics, which proved to be valuable in engineering-related applications as well in the past decade. The main aim of this research project was to exploit the potential of cooperative game-theoretic and mechanism design methodologies to provide new approaches for problems and open questions related to energy markets. The current research focussed on two important energy infrastructure systems: Electricity (and in the wider sense electricity-related) markets and natural gas networks.

2 Results

2.1 Electricity and electricity-related markets

2.1.1 Contextualization of the results

Electricity trading may take place on a diverse set of time scales: From long term contracts, in which e.g. the generating capacity of units is reserved for even years ahead for buyers, to intra-day markets, where the product is delivered only hours after the deal. One of the main aims of these multiple trading platforms is to ensure possibility until the last instance to modify the reported energy needs and generation schedules in order to avoid imbalance in the power system. Regardless of the various allocation mechanisms, due to demand and production uncertainties (the latter especially relevant in the case of renewable sources), imbalances will arise. As these imbalances cause frequency shift in the power network, certain forms of ancillary services (or 'reserves' to put it shorter) are needed for frequency stability. Activating these reserves in the appropriate time restores power balance and thus network frequency. Ancillary markets [11] are specialized energy-economical platforms, in which a broad spectrum of commodities connected to ancillary services are traded.

Day-ahead scheduling of electricity generation is typically organized along the following two principles.

- The unit-commitment approach [10] assumes a fixed demand prediction and aims to minimize the total cost of generation, according to the reported technical and economic parameters of generating units. The problem of reserve allocation may be also included in the unit-commitment framework.
- Day-ahead electricity power exchanges (DAPXs), on the other hand, consider bids both on the supply and demand side, thus they are able to take the price-elasticity of demand into consideration as well. Although the technical parameters of generating units are less emphasized in this framework, special order types, called complex and block orders are present in these markets which aim to address the technical requirements and non-convex cost components (like start-up costs) of these units [14, 9]. Day-ahead electricity auctions are typically

formulated as two-sided multi-unit auction problems, where the aim is to maximize the total social welfare (the total utility of consumption minus the total cost of production) [7]. The scheme of day-ahead markets may be also extended to include not only the coordination of energy but also reserve allocation [5].

Both the above approaches rely heavily on optimization tools, and the computational demands and challenges are significant in either case. In the case of unit-commitment the start-up variables, while in the case of DAPXs the variables of complex orders (e.g. block orders) are represented as integer (typically binary) variables in the computational framework.

In the following, we summarize the scientific contributions of the research project PD123900 in the context of topics discussed above.

2.1.2 Results related to the unit-commitment approach

The problem of the simultaneous allocation of energy and reserve capacities from a unit-commitment perspective is addressed in the conference paper [23]. The proposed methodology is based on the decomposition and piecewise linear approximation of generation characteristics, while the optimization framework is formulated in a distributed manner, making the utilization of parallel computing power possible. A finite number of operation modes is defined for each generating unit, and the feasibility and resulting cost of their possible combinations (operating profiles) is analyzed. Secondary and tertiary reserves are also allocated in the process. A simple heuristic is introduced to reduce the number of operating profiles.

2.1.3 Results related to electricity-only day-ahead markets

The first set of results on the topic of DAPXs corresponds to electricity-only market frameworks, where the allocation of reserves is not considered.

Bid-aggregation
In realistic day-ahead markets the number of participants and thus the number of submitted bids is high (e.g. several thousand or even tens of thousands). As an acceptance variable is assigned to each bid during the market clearing process, the size of the optimization problem may be significant. In the research report [26] we have shown that via the aggregation of simple hourly bids (which are characterized by price-quantity pairs) a computationally efficient market clearing method may be implemented, which provides optimal or nearly-optimal results in the analyzed cases, while reduces the computational time by one order of magnitude. The approach also includes block orders and bids with minimum allocation ratio. The manuscript is currently under revision at the *Hungarian Journal of Industry and Chemistry*.

Minimum income condition orders
Minimum income condition (MIC) orders form a subclass of complex orders, used in practical DAPX implementations (e.g. in the Spanish electricity market). They are supply orders consisting of several hourly step bids (elementary bids) for potentially different market hours, which are connected by the MIC which prescribes that the overall income of the MIC order must cover its given cost. During the research project, the properties of this complex order have been analyzed, and in the journal paper [21] it has been shown that the considering the current computational implementation of this order type, the interplay of multiple MIC order may result in undesired phenomena and open the possibility of strategic bidding in DAPXs.

In addition, also related to the MIC concept, we proposed a novel supply order type for DAPXs (*'flexible production order'*), where multiple, mutually exclusive production profiles are allowed in the bidding process. During the market clearing calculations, only those subset is considered of these profiles, which (under the resulting hourly market clearing prices) fulfills the MIC. The concept has been published in the conference proceedings of the 16th International Conference on the European Energy Market (EEM) [24].

Price-decoupling
The standard model of DAPXs assumes a universal market clearing price for each perid, which (except for complex orders, where paradox rejection is allowed) determines the acceptance and payoff of the submitted bids both for the supply and the demand side. In the current research project, we analyzed the possibility of *'price decoupling'*, where potentially different clearing prices are applied for the demand and the supply side. While, the possible application of this principle in the context of conventional 'pay as clear' markets (as standard European DAPXs) is described in [17], the approach may also be used to design less conventional, two-sided pay-as-bid type day-ahead electricity markets as well [20].

2.1.4 Results related to integrated day-ahead markets

In this subsection we enumerate the research contributions, which are connected to integrated markets, where the allocation of energy and reserves is calculated simultaneously.

Coupling of integrated markets
The basic concept of DAPXs assumes that the trading is not limited by any transmission bottlenecks. If the maximum capacity of power lines is also considered, the concept of DAPX boils down to the problem of market coupling [8]. The problem of market coupling has been extensively researched in the context of electricity-only markets, but literature results corresponding to the coupling of integrated markets are very scarce. In the journal paper [19] a framework for the coupling of integrated markets has been proposed. In this framework the line transmission constraints must hold not only in the case of nominal energy trading, but also when the allocated reserves are activated. In addition, novel bid types are introduced, which consider the physical characteristics of generation units, but allow for a flexible energy/reserve allocation.

The uncertain bidder pays principle
A central question related to reserve allocation is the economic aspect of the process. In other words, since the introduction of ancillary service products, there is a debate about how the arising costs should be covered [15]. In the current practice system operators (typically financed by govermental regulation authorities) pay for the allocation of reserve. An other approach of this question is the following. Reserve must be primary allocated to cover uncertainties. If we can classify the participants of the DAPXs according to their uncertainty level, we may consider their contribution to the resulting uncertainty in the market clearing process. If we accept a bid from a more uncertain production source (e.g. a renewable source), we must calculate with larger uncertainty in the resulting power mix. A possible approach may be to make the 'uncertain bidders' pay for the uncertainty they bring into the system and for the respective reserve allocation costs. One possible implementation of this principle in an integrated DAPX framework is described in the journal article [25], where the concept of supplementary reserve demand bids is introduced, using the principles and computational solutions also utilized in the formulation of MIC orders.

2.2 Natural gas networks

2.2.1 Cooperative game-theoretic approaches

The fundamental concept of cooperative game theory is the so called characteristic function (CF). If we have a set of n players (denoted by N), the CF assigns a real number to each subset of N (called *coalitions*). This number represents the value which may be achieved by the coalition by itself, in other words without the help or cooperation of players outside the coalition. To provide a very simple example, let us consider the following. We may have a game in which the individual players represent buyers and sellers, who can produce any utility (or value) only by trade transactions. In such a case, the value of the characteristic function will be nonzero only for such coalitions, where at least one buyer and one seller is present. Each coalition may be characterized by its members: A particular player may or may not be in the coalition in question, thus the CF may be formally written as

$$v : 2^N \to \mathbb{R} \quad \text{where} \;\; v(\emptyset) = 0 \quad .$$

This description enables us also to analyze the bargaining power of players in the game. If we return to the example mentioned above, we can see that in a setup where multiple buyers and only one seller is present, the bargaining position of the seller is better, since he/she is needed for every coalition where the value is positive. The concept of the Shapley value [12, 3] gives a quantitative characterization of this bargaining power, by calculating the average marginal contribution for each possible coalition to which the player in question may join. Formally, the Shapley value of player i in the case of the characteristic function v, denoted by φ_i may be calculated as

$$\varphi_i(v) = \sum_{S \subseteq N \setminus i} \frac{|S|!(|N \setminus S| - 1)!}{|N|!}(v(S \cup i) - v(S)).$$

Using the above concepts of cooperative game theory and some simplifying assumptions, it is possible to determine the bargaining power of players located in capacity constrained networks, like the European natural gas network. This approach has been recently used to characterize the effect of new infrastructure projects (e.g. new pipelines) on the participants of the European gas market [6]. The research project provided two main results in this context:

- We developed a characteristic function (CF) based framework, which, in contrast to earlier literature results, makes individual flows of coalitional members distinguishable, and also considers liquid natural gas as a source. The proposed framework has been applied to analyze the effects of the project Nord Stream 2 on the participants of the European gas market, and has been published in a research report and a journal paper [27, 28]. The study also considers the effect of shutting down the transit route via Ukraine from Russia to Europe. The results of the work are depicted in Fig. 1.

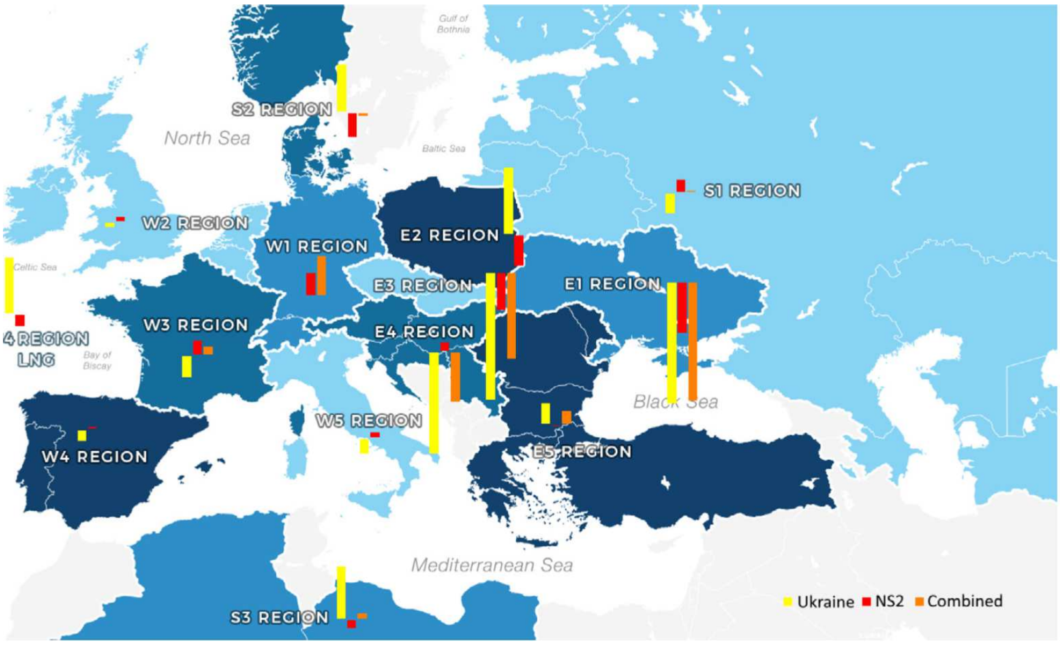

Figure 1: Changes in the Shapley-values of the modelled regions in response to the Nord Stream 2 project, to the shutdown of the Ukraine transit and to the combination of the two according to the model prediction. Figure from Sziklai et.al. 2020.

- Partition function (PF) form games represent a more general setting compared to CF form games. In this setup [16], the value of a coalition is interpreted only as embedded in a certain partition of the player set N. This class of cooperative games are capable of describing *externalities*, where the cooperation of a set of players also affects the payoff of players outside the coalition. In other words, the value of a coalition in PF form games is not universal, but also depends on the partition in which they are embedded, thus the cooperation structure of other players. In the jornal paper [22] a novel methodology has been proposed for the analysis of natural gas networks, which includes the description of third-party access pipelines, considers transfer profits as externalities and formulates the model in PF form.

2.2.2 Mechanism design approaches

Capacity allocation in natural gas networks is also an issue of high importance. As long, as the capacities required for the planned trade transactions do not exceed the pipeline capacities, allocation is simple, and it practically means only administration. However, if the available capacities are not enough to satisfy all participants aiming to allocate capacities in the network, some kind of capacity-allocation method must be used to distribute the available pipeline capacities among participants (players) who apply for them. The first auction, which coordinated the long-term bookings of available existing and future pipeline capacities on the EU-level has been held in 2017 March, on the PRISMA auction platform. During this auction, yearly, quarterly and monthly pipeline capacity products have been auctioned simultaneously using an ascending clock auction (ACA) method. Altogether 2165 unique auctions took place on 6 March for each point and each year. In most of the cases no real competition emerged, and as the result of this auction, the dominant market player (GAZPROM) was able to acquire the great majority of high-importance capacity licenses for in some cases as long, as 20 years (for example, all interconnection capacities on the border of Slovakia have been booked for 20-25 years by GAZPROM). Altogether, it seems that the current capacity allocation method favors big market players. If small or even medium size individual entities (countries or local retailers) wish to ensure a path for themselves to a desired source, they have to bid for the individual components (pipelines) of the path in question one by one, and may end up with no access and unused pipeline capacities as well (if e.g. the price of only a single component of the path becomes too high in the auction process, while they get the capacities for the rest of the path at reasonable price in earlier auction steps). The research report [18] aims to address this issue and proposes a potential novel method for capacity auctioning in natural gas networks (convex combinatorial auction). The efficiency of the proposed method is compared with the currently used ACA method via simulations.

3 Summary

In the work plan of the original research proposal, at least 3 international journal articles and 3 international peer-reviewed conference articles were predicted regarding the publication output of the project. The final publication output consists of

- 5 published SCI indexed journal papers with a total impact factor of 17.37 (the impact factor values of the 2020 and 2021 publications are predicted values) [22, 25, 19, 28, 21], from which 4 include the principal investigator as first author, and 2 are single-author publications. Regarding the Scimago ranking of the journals, *Energy Economics* (where the articles [22] and [21] have been published) is currently ranked 5. out of 126 in the category 'Energy (miscellaneous)', while *Energy Policy* (corresponding to the paper [28]) is ranked 7. in the same category (thus both are D1 journals).

- 4 peer reviewed international conference articles [23, 17, 24, 20] (the PI cancelled the conferences originally planned for the summer of 2020 because of the COVID crisis), all of which includes the PI as first author, and 3 of these are single-author publications.

- 3 research reports/preprints [27, 18, 26], from which [26] has been submitted for journal publication. The manuscript [18] has been submitted to the Commodity and Energy Markets (CEMA) 2020 conference[1] (postponed for the summer of 2021), for which the journal *Energy Economics* provides a special issue.

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