# Simulating producer behavior in congested electricity systems

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# Abstract

Congestion management in liberalized power sectors is a complex multi-actor problem, where technical, economic, social, regulatory, and political aspects all play a role. This paper presents a participatory simulation tool that can be used to evaluate congestion management mechanisms. It was developed to facilitate research related to strategic bidding under congestion and to support education on congestion management. Also, it was developed for the more fundamental purpose to explore the possibilities that social simulation provides for understanding complex behavior in congested power systems. The tool has proven its educational use for four different audiences: energy company managers, students, scientists, and employees of a network operator.

Keywords: Participatory simulation, electricity transmission, congestion management.

# 1. Introduction

# **1.1 Peculiarities of electricity markets**

Electricity is a peculiar good. A lack of storage options means that demand and supply must be balanced instantaneously. Because this permanent balance is fundamental for the functioning of the power system, regulatory efforts are pursued to ensure that the interactions of individual market parties do not jeopardize the system's proper functioning (HOGAN, 1993). As a consequence, electricity markets are *artificial*: participants are surrounded by institutions that limit or otherwise influence the actions they take. Within the limits players may find opportunities to manipulate the system and exhibit market power.

For many decades the electricity sector was considered a natural monopoly. This perspective started to change in the early 1980s and different countries around the world liberalized their power sectors in the years that followed (JAMASB & POLLITT, 2007; CORRELJÉ & DE VRIES, 2008). Liberalization resulted in the creation of markets where electricity could be traded as a commodity. These efforts have led to new questions regarding the regulation of the markets that co-evolved with the physical electricity infrastructure. Electricity infrastructures and markets therefore provide interesting cases to explore new tools, methods, and approaches for social simulation.

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Electricity systems in Europe originally evolved in the context of national borders and have later been interconnected and harmonized across Europe (see Fig. 1). Nonetheless, as DOMANICO (2007) argues, *"the infrastructure has been built to meet national needs and not in anticipation of the internal market*" (p. 5073). According to SUPPONEN (2011) there is evidence that in transmission planning on a European level national interests prevail above common ones. As a result, cross-border capacity in Europe is generally in short supply (BUIJS et al., 2011).



(Image based on OpenStreetMap data (http://openstreetmap.org), rendered by Chris B. Davis) Fig. 1: The interconnected European power system

Electricity markets are peculiar indeed: the physical product is entirely separated from the market in which it is traded. Opposed to many other markets, such as those for apples, oil, or toasters, a buyer in an electricity market does not physically acquire a 'box of electricity' at the time of the sale. Instead, a buyer purchases the service of being supplied a quantity of electricity at a specific date and time in the future, e.g. 100 MW between 9 a.m. and 10 a.m. next Monday. This electricity needs to be produced at that time exactly and can be supplied neither sooner nor later. This implies that sufficient network capacity must be available at the time, so the power that is generated can be delivered to the customer. Electric power, however, only adheres to the laws of physics, and power flows can, in principle, not be steered. The topology and spatial characteristics of the network thus determine what power flows will result when market players in a network produce and consume.

# 1.2 Simulating market behavior

The well-functioning of our electricity system depends on the balance between supply and demand. As 'systems' – in the broadest sense of the definition, i.e. markets ( $CO_2$ , short and long term power markets), physical infrastructures (ICT, energy, transport), institutions (rules and regulations) – are increasingly connected and integrated, infrastructure planning has become more than just managing physical elements and their interactions. Infrastructures have become too large and complex to grasp, understand, let alone predict (CHAPPIN, 2011; NIKOLIC, 2009). Much is dependent on how actors may behave on markets in these infrastructures, leading to questions such as: under what conditions can we expect that market players will behave in such a way that the social cost of having balanced electricity grids are minimized? What institutions could be designed to increase the probability of such conditions? How can we make these interconnected infrastructures less vulnerable for cascading failures? How to learn how these systems function in various institutional and spatial contexts? How could we embark on questions like these?

In this paper we focus on the function of *congestion management* in electricity infrastructures. The technical measures to manage congestion in power grids are the result of actions taken by independent market parties, none of which is individually able to oversee the system as a whole or responsible for the consequences. Congestion management must ensure that the behavior of all market parties combined leads to technically feasible network flows.



Fig. 2: Example: technical function of congestion. A and B are transmission networks, connected by a 1000 MW connection.G1, G2, G3 are generators and C is a consumer.

An example of this is shown in Fig. 2. The line connecting A and B is capable of transporting 1000 MW, so it would be overloaded if generators G1 and G2 would simultaneously produce at full capacity. The technical function of congestion management is conceptually simple: it must ensure that the combined production of generators G1 and G2 is limited to 1000 MW, while still meeting the demand of consumer C.

Multiple outcomes are technically feasible. For instance, G1 or G2 could reduce its output to 0 MW, G1 and G2 could decide to each limit their production to 500 MW, or they could agree upon another division under which the generation of G1+G2 does not exceed 1000 MW. From a social perspective it is desirable that the eventual solution is not only technically feasible, but that it also comes at reasonably low cost (and, perhaps, has the least environmental impact, although we will not consider this for the sake of simplicity). There are various mechanisms available that seek to ensure that the actions taken by market parties eventually lead to an outcome in which supply meets demand within network limitations (see section 2).

The above shows that the *behavior* of actors is key to answering this question. Therefore, in this paper, the main question is:

"Can a participatory simulation be used to increase the understanding of behavior of producers in congested power systems?"

In this paper, we describe a participatory simulation that is developed in order to capture the behavior of market participants under various systems and conditions. The participants learn how these systems for 'managing' congestion in power infrastructures work and we learn about the outcomes on the system level.

#### 1.3 Structure of the paper

In the next section, some elements of congestion management – including the opportunities for participants gaming congestion mechanisms – are discussed. These form the interesting ingredients for a participatory simulation. Afterwards, the participatory simulation is described. In the fourth section, the experience with the simulation is described. We end with conclusions and an outlook.

#### 2 Congestion management and gaming

#### 2.1 Congestion in the power sector

In the liberalized European electricity sector, producers can individually decide where and how to generate power, depending on the result of trading that has taken place in one or multiple types of markets (MEEUS et al., 2009). The aggregated dispatch decisions result in network flows that are determined by the physical laws of electricity (HOGAN, 1993). The system operator is responsible for investing in the infrastructure that is needed to transport this electricity. He must ensure that the grid is operated in a stable and safe manner, but there is a tradeoff between investment cost and societal benefit of having the grid in place. Therefore, in a socially optimal grid, it is possible that flow patterns sometimes exceed the capacity limits of (parts of) the network. Because overloading the network may result in outages or physical damage to the components, it is essential that the system operator takes measures to prevent this overloading (KUMAR et al., 2005): we label this task as congestion management.

In a technical sense, power output has to be decreased in a region with surplus generation in excess of the available transmission capacity, whereas it must be increased elsewhere in the system, because total generation must match consumption. The objective is to do so at the lowest cost possible by ramping down the most expensive plants while using the cheapest plants (that are still available) to provide the compensatory power. If the system operator knows the production costs of all connected units, such as is the case in a vertically integrated system, this is a conceptually easy (but mathematically often highly complex) task. Since liberalization this is no longer the case in Europe, however: this information now solely resides with the (independent) producers.

In order for the system operator to alleviate congestion at the lowest possible cost, producers must somehow reveal their costs or otherwise ensure that congestion is alleviated efficiently. There are various mechanisms available<sup>3</sup> for system operators to provide market signals that enable network users to respond by taking actions that alleviate congestion in the most efficient manner. Although these methods are equally well able to (economically) efficiently alleviate congestion in theory, there are differences regarding the allocation of the resulting congestion costs, information requirements, and responsibilities, which may cause different outcomes when the methods are applied in reality.

The game that is discussed in this paper primarily deals with situations in which market parties do not take the economically most optimal actions (i.e. due to a lack of information or transaction costs) or deliberately try to 'game' the system (i.e. increase profits at the expense of others).

# 2.2 Gaming congestion mechanisms

Because power outages impose large costs on society and overloading the network is not an option<sup>4,</sup> it is crucial that congestion is alleviated by shifting production from one location to another. The actors that are capable of (contributing to) alleviating congestion thus find themselves in a powerful position: they know that the system operator is willing to pay a high price in order to avoid the extreme cost associated with failing to alleviate congestion – i.e. the system operator must agree to a contract for the service 'alleviate congestion' VAN BLIJSWIJK, 2011. The fact that congestion must be alleviated can be used by producers to artificially increase the price of this service (depending on the congestion management mechanism that is applied), at the expense of the system operator.

#### 2.3 Approach for exploring congestion management mechanisms

The opportunities for generators to bid strategically differ under the mechanisms, depend on the characteristics of the situation, and are affected by the interactions that take place when multiple producers behave strategically. When this is the case, VAN BLIJSWIJK (2011) argues that generators must outbid each other in order to obtain additional strategic bidding revenues. Therefore, we need to use an approach that is capable of capturing the variety of decisions that can be made by those involved and together drive system outcomes.

A variety of options to game congestion management mechanisms is described by HAKVOORT et al. (2009). They provide examples of strategic bidding strategies and calculate the financial benefits that can be obtained by generators, but do not consider the interactions that may take place when multiple parties seek to 'game the system' at the same time. Veit et al. (2009) used an agent-based model to simulate strategic bidding under congestion in the German electricity system that incorporated the *reinforcement learning algorithm* developed by EREV & ROTH (1998):

"Agents are capable of learning from past experience through a modified version of the *Erev* and Roth (1998) reinforcement learning algorithm that was shown to be especially suitable for electricity market simulations by Nicolaisen et al. (2001). The algorithm is non-deterministic and was designed to mimic human learning behavior in games." (VEIT et al., 2009, p. 4134)

The authors suggest that further research should address one of the limitations of their work, namely that "*the learning algorithm should be further adapted to improve learning outcomes*" (VEIT et al., 2009, p. 4143). In order to sufficiently these elements, we take an approach that includes human input to design these algorithms.

<sup>&</sup>lt;sup>3</sup> See e.g. KRISTIANSEN (2007) or VAN BLIJSWIJK (2011) for an overview of options.

<sup>&</sup>lt;sup>4</sup> For the sake of completeness, we must mention that there are in fact circumstances under which the network can be slightly overloaded for a limited period of time. We do not consider these in this paper.

# 3 Model description

#### 3.1 System representation

Our participatory simulation model simulates two interconnected electricity systems ('North' and 'South'), each of which has a mandatory power pool. This is depicted in Fig. 3. Players take the role of a power producer and offer capacity to these spot markets for a single hour. They specify the volume they are willing to sell at which price. The tool then clears these markets using the selected congestion management mechanism while assuming a perfectly inelastic demand curve (demand can be set by the game manager). On the basis of the accepted offers the model calculates production for each of the regions and the resulting power flows between them. If this would exceed the network limit, which can be set by the game manager, the selected congestion management mechanism is used to alleviate congestion.



Fig. 3. The modelled system

After every round the tool calculates revenues and costs for each player. Their objective during gameplay is to maximize profit and have a larger bank balance than the other players. This can be achieved by outperforming others with respect to how to place optimal bids – in the regular market and, particularly, when congestion management is applied. Table 1 below presents an overview of the revenue and costs elements that affect players' bank balances in the game.

Revenues	Costs
Power sales	Fixed power plant cost
Constrained-on power sales	Variable (fuel) cost
	Constrained-off power sales
	Interconnection capacity cost

Table 1: Revenue and cost elements. Note: constrained-off power is listed as a cost to producers, because they are in theory willing to pay the system operator to ramp down their plants as they avoid their variable costs by not having to produce

### 3.2 User interface

There are two separate user interfaces: one for the game manger, which includes the overall game controls and shows market data at the end of each round (and should be visible for all players on e.g. a large screen; screenshot provided in Fig. 4), and one for the players, which contains the information about and the controls for each production unit (shown in Fig. 5).



Fig. 4: Operator interface



Fig. 5: Player interface

# **3.3** Power plants

Users play the role of a power producer with three 1000 MW power plants. These can be of the type wind, nuclear, lignite, hard coal, new natural gas (higher efficiency), or old natural gas (lower efficiency). Each of these generation technologies has different fixed ( $\notin$ round) and variable ( $\notin$ MWh produced) costs.

#### 3.4 Congestion management mechanisms

The tool allows for simulating three different congestion management mechanisms: basic system redispatch, explicit capacity auction, and market splitting. It is also possible to simulate a system without congestion or without any interconnection capacity. See e.g. KRISTIANSEN (2007) or Van Blijswijk (2011) for details regarding these congestion management methods.

#### 3.5 Software

One of the main considerations for deciding on which software to use was the requirement that the game could be played by separate players within a network. NetLogo was used because it is a commonly used tool for social simulation and provides multi-user functionality out-of-the-box.

#### **4** Applications and experience

We applied the simulation before four different audiences. In this section we describe the setup of, and experience in, these sessions and the lessons learned.

#### 4.1 Case 1: Energy company managers

The game was played with a group of 6 managers at an energy company as part of a lecture on congestion management methods. Each participant had a laptop that was connected to a local network. The game was played in an integrated manner with a lecture, which covered different congestion management mechanisms. Each time a mechanism was theoretically introduced, the participants played 3–4 rounds of the game in which this mechanism was applied. This allowed the participants to directly experience the theory they had just been taught.

Some of the congestion management methods were played offline: they were not yet part of the simulation and had to be performed with the help of a spreadsheet (or a piece of paper, a pencil, and a calculator). These methods were added to the functionality of the simulation after this instance.

Both the participants as well as the operators found that the simulation provided a useful tool to better convey the core learning objectives to the audience. An informal evaluation showed that the simulation allowed the audience to experience (the consequences of) the theoretical notions that were explained, allowed for more interaction, and a deeper understanding.

# 4.2 Case 2: Academic staff

After implementing the congestion management mechanisms in the simulation that were previously performed off-line, six staff members of the Energy & Industry Section (E&I) of Delft University of Technology were invited to participate in a session. The participants already had considerable expertise with power markets and were interested in learning about the specifics of congestion management mechanisms. All three methods were simulated during a session of  $\Box 25$  rounds. This allowed for observing strategic learning effects. Some players tried to artificially increase their profits by adjusting their bids over time. As with the previous case, the players found the game to be an effective tool to learn about congestion management.

Feedback from the participants led to a number of usability improvements, particularly with respect to the ability of the software to notify users of the simulation's progress and by informing them about the required actions.

# 4.3 Case 3: Master students

The third case was with a large group of Master students, as a part of a course on electricity and gas markets. A group of 40 students attended the lecture and participated in pairs. After a short introduction to the simulation tool and two practice rounds, the participants had to switch between theoretical learning and applying the theory in simulation. Each of the three congestion management mechanisms was played for 3–4 rounds. This was enough to provide a basic understanding of the dynamics of the methods. However, these constraints limited the opportunities for observing strategic bidding by the participants.

During this session we frequently observed participants behaving irrationally. Participants who did not understand the concepts of electricity markets sufficiently displayed such irrational behavior that the game did not converge to the theoretically expected outcomes. In some cases, the results were even opposite (i.e. power flows from the expensive to the lower-priced country). Time prohibited us from more extensively covering the basics of power markets and the reasons that lie at the basis of producer behavior under different congestion management mechanisms in theory.

# 4.4 Case 4: Network operator

At the time of writing, the most recent instance of applying the simulation was during a session with employees of a network operator. The tool was used in a fashion similar to earlier applications, i.e. in combination with a lecture on congestion management. Most participants were familiar with the practical application of congestion management already, particularly with respect to the method that is used in the Netherlands. The aim of the session was therefore to approach congestion management from a theoretical perspective, thus disregarding a number of aspects that play a role in practice and which were known by the audience. This provided the audience the opportunity to experience the fundamental issues that were often at the basis of policy decisions regarding congestion management.

# 4.5 Experience and response

In general, participants in all four sessions were positive about the ability of the game to support teaching. Most described it as 'fun' and effective, although it took most of them a little while to understand the interface of the tool. Also, a basic understanding of the functioning of power pools is required to play the game.

A couple of rounds per method is sufficient for a basic understanding of the implemented methods. More rounds are required if one aims to use the simulation as a tool to explore effects of strategic bidding by players. Consequently this is only possible if a considerable amount of time is available (>2 hrs). For interesting gameplay it is advisable to include at least 8 power plants (players) in the simulation, but the simulation is considerably slower in case of large groups of users (>20 PCs). In case of too few players, it is possible to let them run multiple instances of the simulation in parallel. Alternatively, the game manager can run a number of instances which behave perfectly competitive as to not disturb the gameplay of the other users.

Although the sessions were not set up with the intention to thoroughly analyze how the participants could bid strategically, we did notice that some participants tried to increase their revenues by adjusting their supply offers. This was done both by withholding capacity and by offering at an increased prive level after having bid competitively in previous rounds.

#### 4.6 Future work

We expect to address the following elements in the near future:

1) allow players to have a portfolio of generation units of different technologies and in different locations at their disposal,

2) include the significant influence of important additional technical constraints that affect market clearing procedures, such as generator ramping constraints, start/stop costs, and specific location, and 3) coupling with a load flow network model, to simulate real situations.

Once these elements are incorporated, a number of experts could be invited (again) to play the game for a number of rounds, in which all input parameters are carefully controlled so the effect of continued playing of the game on player performance can be measured. The results of this effort are expected to be twofold:

we can assess the opportunities for strategic bidding given a particular (existing) situation, and
the strategies applied by real players can be used as input for the design of agents in agent-based models of the power sector, where congestion management is included in the research scope.

#### **5** Conclusion and outlook

Electricity is a peculiar good. Its physical characteristics require actors to adhere to common standards for the system to function properly. Congestion management is a key function of the system: its objective is to achieve optimal dispatch of power plants in the short term, considering network limits which cannot be exceeded. This function is not straightforward, because of limited or asymmetric information, the physical nature of electricity, and a multi-actor setting.

This paper presents a participatory congestion management simulation tool, which we developed 1) to facilitate research on strategic bidding under congestion,

2) as an educational support tool for teaching about congestion management, and

3) to explore the possibilities that social simulation provides for understanding complex behavior in congested power systems.

# 5.1 Experience

The simulation has been used with four distinct audiences –energy company managers, Master students, academic staff, and employees of a network operator– and was well-received with respect to its ability to support education about congestion management. When some additional elements are included –portfolios of units, inclusion of relevant (technical) constraints, and coupling with a load flow network model– it can be played with a number of experts to evaluate strategic bidding under congestion.

#### 5.2 Conclusion

Our experience with the application of the game suggests that participatory simulation can indeed be used to explore the behavior of producers in congested power systems. The most prominent observation is that the game is a useful tool to support learning about congestion management. At the same time it allowed us to observe the behavior of various types of players in a hypothetical electricity system where congestion may occur. Indications of strategic producer behavior, by withholding capacity or bidding at elevated price levels in order to increase players' revenues, have been observed. The opportunities for strategic behavior and the consequences for mechanism design have not yet been systematically analysed with the game.

We have, however, identified three limitations that are inherent to the use of a simulation game for the purpose of improving our understanding of producer behavior in congested power systems:

- System-specific opportunities for strategic behavior The devil is in the details: a game that is too much abstracted from reality will not capture the actual strategic behavior that is made possible by specific details of the congestion management method when applied in reality. An example is that in our game, the system operator was allowed to accept parts of bids, whereas in the reality of redispatching (at least in the Netherlands), block bids are submitted which the system operator must accept in their entirety.
- *Scope limitations* While including the details of realistic congestion management methods is important for understanding real-life behavior, it takes much programming time, and makes the game difficult to understand and highly situation specific, as the details of congestion management mechanisms vary per country (power system).
- *Time constraints* Power markets in general, and congestion management specifically, are so complex that lay people such as college students have difficulty grasping the game and the link it with the reality it represents. As a consequence, there is a learning curve before they begin to exhibit rational, strategic behavior. On the other hand, playing with professionals poses limitations as well: firstly, their willingness to lend their time and, secondly, one may question whether they do not behave strategically in the game in the sense that they may not be willing to reveal their true strategies.

# 5.3 Outlook

Despite these reservations, we believe that there are nonetheless good reasons to continue with the development of the game:

- *Not bound to reality* It provides the opportunity to gain an insight in the possible behavior of market parties under circumstances that are different from the current market. It is thus an important tool for evaluating new congestion management mechanisms, or changes to existing schemes.
- *Lack of information* Without it the only party that would be able to evaluate producer behavior would be the TSO itself, as it is the only actor that has access to the results of applying congestion management.
- *Educational effectiveness* It has proven to be useful for educational purposes, although a simpler, less detailed version is expected to be much more effective for most audiences.
- *Fundamental research on strategic behavior* A simple, perhaps more abstract version could potentially yield results that are not directly applicable in practice, but are nonetheless interesting from a scientific point of view when dealing with strategic behavior of actors in a more fundamental way.

The simulation tool we developed addresses the complexity that arises from congestion in infrastructures. We believe it can contribute to research in the field of power system development in the Netherlands, Europe, and possibly elsewhere, which eventually allows us, as a society, to adequately develop the infrastructures we need to achieve the goals we strive to achieve.

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