Strategic Behavior in Liberalized Electricity Sectors:

Game Theoretical Formal Modeling in Policy Analysis

Sertaç Oruç
Delft University of Technology
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Strategic Behavior in Liberalized Electricity Sectors:

Game Theoretical Formal Modeling in Policy Analysis

Proefschrift

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I dedicate this dissertation to Çağla,
lifelong friend of mine and the mother of Şiraz.

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Sertaç Oruç,
Delft, October 2014.

Contents

Chapter 1

Introduction

1.1 The war of liberalization

Since its invention, electricity has been the subject of harsh debates, dating back to the infamous 'War of Currents' between Nikola Tesla and Thomas Edison (Jonnes, 2004). On the one hand, Edison and his company General Electric wholeheartedly promoted the incumbent direct current (DC) power distribution system, giving various state-of-the-art DC-compatible technologies of the time as an argument against the novel alternating current (AC) power distribution technology. Indeed, DC electric motors and lighting, which were the ground breaking novel technologies of the day, were compatible only with DC current; there were no practical alternatives available until the 1880s. Various technologies, including electricity meters, motors and lights were designed solely for DC power. Moreover, AC power was advertised as a notoriously dangerous technology, quoting the alteration of current was far more hazardous to heart rhythm than DC current at comparable magnitudes.

On the other hand, Edison's European counterparts pushed hard for AC system. Sabastian Ferranti, an engineer at Siemens Brothers in London, pioneered early AC power technology. Furthermore, Guillaume Duchenne, Lucien Gaulard and Galileo Ferraris made marvelous contributions to AC technology, such as the demonstration of AC power usage and the development of the AC motor. All these developments advancing AC technology were sealed with the electrification of the Italian capital Rome in 1886 by the Ganz Works company, which proved that it can be used efficiently in large scale electrification. This gave AC technology a major impetus, and from that point on it gained ground against DC technology. Westinghouse, a keen venture capitalist from Pittsburgh, captured the AC flag from its European pioneers by acquiring North American rights of their AC patents as well as an AC motor patent from Nikola Tesla. This smart move teamed up Tesla and Westinghouse against Edison and General Electric in the 'War of Currents'.

Surprisingly, the war did not involve only technological pros and cons of these two competing technologies. Edison carried out several public relations campaigns to discourage the use of AC in state legislatures by presenting AC as a dangerous technology (Brandon, 2009). He even recruited technicians to demonstrate the deadly power of AC and tried to convince the public that AC is more dangerous than his DC system (Brandon, 2009). He coined the term 'westinghoused' in place of 'electrocuted'. Ironically, it was Edison himself who invented the first electric chair for the state of New York as a byproduct of the efforts to bash the AC system.

Despite all the efforts from the Edison side, the outcome of the war was determined decisively in favor of the AC power system. The fact that AC systems can be much more economical in transmitting power over long distances gave it the essential edge to succeed. However the legacy of the DC system partially remained until the the 21^{st} century. New York City, which was the battle ground of the war, had already invested in a number of DC installations by Edison. These installations continued to work for decades in parallel with the growing AC network. Some of these installations remained until 2007 (Lee, 2007).

As can be understood from this brief history of the War of Currents, the management of the electricity system does not depend solely on the technical advantages of the competing technologies but also on the institutional setting. In this institutional setting, competing firms take part as 'player' who sometimes try to 'game' the situation by enacting 'strategic behavior'. States and governments take part as 'policymaker', which make legislations to mitigate strategic behavior; the electricity system presents itself as the battle ground of these strategic games.

Unlike conventional goods, electricity shows some peculiar characteristics which have always made it an interesting subject for the technology management discipline. The fact that it is transmitted from the generator to the end consumer at approximately the speed of light, and the fact that it cannot be stored economically, are only two of these special characteristics. With respect to various perspectives, from security and safety to operational and economical efficiency, these characteristics demand a high level of coordination and sophistication. Hence, a pseudo-military level of command and control management was seen as essential up until the late 1970s. More than a century after the 'War of Currents', the 1980s saw the beginning of a new strategic war, i.e., the 'War of Liberalization'.

Until the 1980s, electricity sectors were managed by either public or private monopolies all over the world. These monopolies dealt with all sorts of operations and aspects of electricity sectors, from generation to retailing and services. From the purely operational level to the strategic management level, electricity sectors were managed in close coordination, i.e., all the activities from generation to retail and services were orchestrated within the same institution. This unity of the sector is referred in the literature as 'vertical integration' in the literature. Vertical integration enabled both the short-term and long-term management of the whole system. The system could be altered almost instantaneously in emergency situations, which can occur in any phase of the value chain, from generation to retail. Similarly, it was possible to optimize long term central planning: the policymaker, usually a board of directors of the national monopoly, was able to make informed decisions about the generation capacity based on diverse data. This data was transparent within the institution, including transmission capacity utilization, transmission capacity planning and demand trends.

During the late 1970s the liberalization ideology started to infiltrate into electricity sectors just as it did in the other public sectors, such as telecommunications, air transport, postal services, gas, water and rail transport, all of which were classically deemed government services. In Europe there were various motivations and drivers for liberalization, such as the weakening competitive power of Europe in relation to the US and China and the integration of nations within Europe under the European Union project. Although the main scope of this research does not include motivations behind liberalization in Europe, an brief account of liberalization history can be found in Chapter 2.

Since the early 1980s, nations all over the world have engaged in a liberalization race to unbundle the vertically integrated institutions which run electricity sectors. Liberalization has never been a one-time operation but rather is an evolving process. The process has been theorized by many scholars (i.e., Green and Newbery (1992); Joskow (1998); Newberry (2002); Vogel (1996)) forming recipes for the nations that take on this mission. The national monopolies and the respective sectors were prescribed to be turned into competitive firms by certain steps such as unbundling, deregulation and re-regulation. All these steps to turn national monopolies into competitive markets have required a thorough institutional change of the management regime of the sector, triggering severe and unprecedented problems alongside the foreseen advantages. These disadvantages are discussed more broadly in Chapter 2. Among other concerns, the ‘strategic behavior’ of new market participants has been a downside of liberalization. As an example, in the new regime a generator may withhold electricity generation capacity, thereby decreasing supply in order to drive up electricity prices for its own financial benefit.

1.2 Strategy and strategic behavior

In this thesis, the term ‘strategy’ refers to the course of actions that a player can take. Basically it is possible to refer to any move or set of moves a player can take as a strategy. Such usage of the term is in line with the strategy definition in game theory literature. In this regard strategy is clearly a neutral term.

As far as the term ‘strategic behavior’ is concerned, it is possible to find out various connotations and meanings in the literature. As an example, for new institutional economists, such as Oliver Williamson, strategic behavior has clearly a negative connotation. In (Williamson, 1999), Williamson notes that

> “Transaction cost economics goes beyond the orthodox description of simple self-interest seeking to include strategic behavior – which manifests itself as adverse selection, moral hazard, and, more generally, as opportunism.”

In other sources, strategic behavior might have a neutral connotation simply underpinning the actions of an actor for self-interest. According to OECD (1993), strategic behavior is :

> “[T]he general term for actions taken by firms which are intended to influence the market environment in which they compete. Strategic behavior includes actions to influence rivals to act cooperatively so as to raise joint profits, as well as noncooperative actions to raise the firm’s profits at the expense of rivals.”

In this research the term is used in a similar sense. Essentially a particular behavior is strategic as long as it intends to influence the market environment for self-benefit. Despite the term is not explicitly negative, some particular strategic behaviors are denounced as ‘adverse’ in this thesis. Although it can be difficult, even impossible at times, to prove a particular strategic behavior as adverse, adversity can be claimed in a narrow sense, especially in formal models where the impacts of the actors can be quantified.

According to the OECD definition, there are two modes of strategic behavior: cooperative and non-cooperative. In capitalist economies, a free market is free as long as the firms abide by the competition rules. Thus there are various ‘don’ts’ that constrain companies. In a market, firms cannot collude to form a monopoly. Collusion between the market participants for mutual advantage at the expense of the benefit of the market is an example of cooperative strategic behavior. Yet cooperative behavior is not the only way to artificially manipulate prices. In electricity markets, withholding generation capacity to push prices higher is one example of non-cooperative strategic behavior. Price predation and the creation of artificial barriers of entry are some other examples. All in all, strategic behavior can have negative connotation from the perspective of the public welfare as well as in term of the health of the market. In the context of electricity markets such behavior may translate into higher prices, less innovation and even severe black-outs.

Strategic behavior can be observed in any market design, whether or not it is a networked industry. Regular strategic behavior such as predatory pricing, collusion or adverse selection might occur when there are only a few market participants, when the market incumbents have established positions or when an information asymmetry between the firms exists (Heuvelhof et al., 2009).

Apart from the regular types of strategic behavior such as the ones mentioned above, there is another mode of strategic behavior, which depends on the network characteristics of the infrastructures. Based on the categorization by Heuvelhof et al. (2009), network-based strategic behavior can be listed as follows:

1. Strategic use of rules:
   This is the strategic behavior that is related to the practice of attaching a particular meaning to some wording in a legal document such as public regulations, organizational rules or contracts for the benefit of one’s position in court in a conflict situation.

2. Strategic utilization of intertwined relations with the government agencies and other actors:
   In many situations of liberalization, the unbundled company has ties with the government and the other nascent companies which are created by the unbundling. The relationships between the management of these newly created entities usually and naturally stay constant, which may cause collusion between these parties.

3. Strategic use of control over crucial technical facilities:
   In some cases, since it is costly to build up rival infrastructures, the operator of the technical system is the same as the incumbent company in the market. The abuse of control over the technical system may give noncompetitive advantage to the incumbent. However, in the electricity market, this can be mitigated by creating independent transmission system operators.

4. Strategic use of the essential and indispensable nature of infrastructural utilities:
   The infrastructures have a crucial role in the functioning of society and are very critical politically. This gives the players, especially the incumbent, immense power that can be abused against the regulator in case the policymaker wants to make a price-related, institutional or operational intervention in the sector.

5. Strategic use of the ‘time’ factor:
   Timing related to the implementation of legislative procedures is very important in promoting or discouraging competition. The incumbent can delay or speed up the procedures by putting firth false arguments and not being accused because of information asymmetry. Hence, playing with time is a fruitful strategy for incumbents: waiting until the possible entrant changes its position such that they are interested in entering the market.

6. Strategic use of financial resources:
   The incumbents usually have very strong financial power compared to new entrants. Although they can make larger investments in better infrastructures and quality service, this may be not enough to protect their dominant positions. Technical or business innovations can lead smaller companies to succeed in taking market share. However the incumbents can also use their financial power to acquire these small and successful companies. This behavior is observed widely in networked as well as non-networked industries.

7. Strategic use of information asymmetry:
   As with the strategic use of financial resources, this mode of strategic behavior is seen both in network and non-networked industries. What makes it crucial in this context is the fact that information asymmetry is a frequent phenomenon in networked industries due to the additional complexity caused by the network. The strategic use of information asymmetry usually occurs in combination with the other types of strategic behavior.

In this study, some of these network-based strategic behavior types are discussed. In Chapter 5, one can see an example of the strategic utilization of intertwined relations with other actors. This chapter shows that sharing a common wholesale market leads to an inefficiency in load-shifting incentive schemes due to free riding behavior. In Chapter 6 another network-based strategic behavior, strategic use of financial resources, is examined as the players game the financial transmission rights market by using asymmetric knowledge. The behavior discussed in this chapter also exemplifies strategic use of information asymmetry.

The belief in the prevalence of adverse strategic behavior can be at times widespread among journalists and public opinion. However, in practice, it is quite difficult to judge a certain behavior as being adverse strategic behavior from a legal and academic perspective. This is mainly due to the fact that it can be very difficult to find evidence. The thin line between strategic behavior and proper competitive behavior is drawn by the intentions of the firm, which are generally not disclosed by the perpetrator of the adverse strategic behavior.

Analyzing strategic behavior is not a straightforward call with regard to non-networked industries. Adding the complexity of network structure makes it even more complicated. There is no universally successful method for correctly understanding and determining adverse strategic behavior. In competition law, conventional market concentration is considered an indicator of market power and hence of potential adverse strategic behavior. In a perfect market, market power is desired to be non-existent and no firm is desired to have the power to manipulate the prices. Thus, the market competition authorities all over the world, including ACM[1] in the Netherlands, watch for concentration of the markets in order to control potential adverse strategic behavior. However market concentration alone, which is usually indexed with standard indicators such as Herfindahl-Hirschman Index (HHI), does not provide the whole picture when it comes to strategic behavior. Since market power is not the only source of strategic behavior, market concentration is not the sole method for understanding and analyzing strategic behavior. The analysis of strategic behavior has to be done with rather ad-hoc methods that take in to account the peculiarities of the underlying system, such as the electricity system in this research. This study proposes a game theoretical formal modeling approach as a means to analyze strategic behavior in electricity sectors. This is explained further in the next section.

1.3 Aim and approach of the research

The large-scale change in the institutional and regulatory settings in electricity sectors has raised new concerns. The change from a mono-actor institutional setting to a multi-actor one means more independent players in electricity sectors in general. Strategic behavior of these new players, as well as incumbent players, has become one of the main concerns regarding the new regime, besides both operational and coordination related concerns. Complexities due to the network-based physical system, coupled with the complexities of newly introduced institutional mechanisms, provide a breeding ground for strategic behavior. The main aim of this research is contributing to the understanding of strategic behavior in liberalized electricity sectors . The strategic behaviors caused by the network characteristics of the electricity system are the prime focus.

In determining the existence of market power, market concentration indices such as HHI may be a blueprint that can be applied to any market without taking the characteristics of the industry into account. On the other hand, in analyzing strategic behavior in networked industries, there is no one-size-fits-all method. The characteristics of the industry should be considered when thinking about strategic behavior. A ‘modeling’ approach can be helpful for incorporating various characteristics of the subject industry. Industry-tailored models can reveal some potential strategic behavior. In this research ‘game theoretical formal modeling’ is chosen as the methodology with which strategic behavior is analyzed. This choice is further motivated in Chapter 3.

The research aims to answer the following main question:

> *How can we understand potential strategic behavior in liberalized electricity sectors by utilizing game theoretical formal modeling?*

The question entails various subquestions, which are addressed and answered throughout this thesis.

The first of these, “What do we mean by strategic behavior?”, is answered in the preceding section. Why we need to enhance our comprehension of strategic behavior is further

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[1] *The Netherlands Authority for Consumers and Markets (ACM)* is a new competition regulator in The Netherlands, which was formed by the merger of *The Netherlands Consumer Authority*, *The Netherlands Competition Authority (NMa)* and *The Netherlands Independent Post and Telecommunications Authority (OPTA)* on 1st of April 2013.

substantiated throughout the thesis. It is important to note that strategic behavior has a negative connotation and needs to be minimized in policy measures. Companies have to be smart to survive in a competitive market. Strategic behavior done by the companies for self-benefit is also in general smart, ambiguous and not easy to be tracked. However once the self-benefit harvested by the strategic behavior conflicts with the global benefit, which encompasses both the benefits of the players in the market and the benefit of the consumers, it has to be hindered by appropriate mechanism design. Such strategic behavior is referred as adverse explicitly in this thesis.

The second subquestion is “Why do we use models and specifically game theory?”. The playing field of this research is the liberalization process in electricity sectors. The holy grail of the liberalization process is to form a totally liberalized, self-governing, competitive market, which is unrestrained from corrective government interventions. However, during the transition period to this goal, the process has required various policy interventions, as explained further in Chapter 2. The research is concerned with these policies and the results of them. We see the transition from national monopolistic markets to liberalized markets as a high-scale, high-cost and unprecedented experiment. It is almost impossible to conduct experiments or trial-and-error methods to be able to see the implications of various policies under such circumstances. Efforts to experiment in this process are either inapplicable or very expensive. Due to the lack of real-life field experimentation, a natural way to understand and tackle the problems associated with liberalization and strategic behavior is modeling the system mathematically and computationally. Mathematical and computational models are cheap alternatives to real-life experimentations. Furthermore, unexpected insights into the problem can be obtained by modeling and simulation.

“What exactly is the methodology that is utilized in this research?” is the next subquestion. The main aim of the research is formulated as ‘understanding potential strategic behavior in liberalized electricity sectors’. Since strategic behavior has different embodiments in different parts of liberalized electricity sectors, a case by case approach is applied in this research. We identify different strategic behaviors in different segments of electricity sectors. Thus the approach in examining strategic behavior begins by framing particular behaviors in their separate contexts. For each case, a context of the strategic problem is provided and a game theoretical formal model is created in order to quantitatively conceptualize and represent the strategic problem. Finally, the model-based analysis with a qualitative discussion that boils down to some insights and lessons about that particular strategic behavior follows up. Three cases are selected that are brought up in relation to liberalization in electricity sectors. The details of the research choices and the research design can be found in Chapter 4.

An implicit question following the above reasoning is “What examples of strategic behavior exist in liberalized electricity markets?”. This is a valid question that drives us to various cases, each of which investigates another strategic behavior in the electricity markets.

Referring to electricity markets actually more than one market are being referred in this thesis: the electricity wholesale market and the electricity retail market. Each of these two markets are featured in the cases in Chapters 5 and 6. The third case proceeds with a more general perspective on electricity sectors. This case investigates the innovation incentives in electricity sectors. The motivations for the choices of the specific cases are further elaborated in Chapter 4.

In each case, the following research questions are investigated:

- Who are the players/actors in each case?
- What are their interests/strategies?
- How can they exert strategic behavior?
- What are the relevant features of the dominant mechanism that describe their strategic interaction?
- How can one model their respective strategic behaviors?
- What kind of insights can one gain from this model, based on the various scenarios that are formulated according to the strategic behavior of the players?
- Considering these assumptions, the model and the analysis, what kind of recommendations can be derived for the policymaker?
- What do we learn from the case in relation to the main question of the research?

Game theoretical formal modeling is the modeling choice in each case. Game theory, being the analytical study of mathematical models of conflicting and/or cooperating actors (i.e., players), qualifies to be able to test strategic behavior in this realm. These models capture the critical features and aspects of the issue to be examined and leave out the tangential aspects. By using an 'exemplifying models' approach (Rasmusen, 2007) the policymaker can take the message by understanding the crux of the model without the complexities that may arise with more complicated modeling techniques such as Agent Based Modeling or closed box simulations. The choice of game theory as the modeling method is further justified in Chapter 3.

A fourth question is "Who is the policymaker?". Although the research refers to the specific problems in the electricity sector liberalization in Europe, the models presented in this research are universal and do not bear specificities of location and political structure. Hence, the policymaker could be any governmental body that has authority to enforce rules upon the market. This could be the national competition authority, unions of nations (e.g., the European Union), the national governments or any political structure that has the right to enforce the laws. This question is specifically addressed in different contexts (i.e., in each case) throughout the thesis.

1.4 Scope of the research

The general aim and approach of the research were specified in the preceding section. Before elaborating on the liberalization process in the next chapter, the scope of this research in an attempt to make clear what is to be expected and what is not to be expected from this research is provided.

The electricity system that is chosen as the research field is mainly composed of a technical and an institutional subsystem. The liberalization process has been changing the institutional subsystem. Because of the close coupling between these two subsystems, analysis of both in the same framework is inevitable. The technical electricity system forms the basis of the electricity market. All the economic activities are built on the technical system. Hence, in order to focus on strategic issues, it is of utmost importance to build an integral view of the technical system. Although comprehension of the technical system is necessary, it is not sufficient for the purpose of understanding various issues related to the ongoing paradigm shift in this techno-economical system. The institutional layer of the system has to be modeled, since this is the main part that is affected by liberalization process.

This research addresses issues at the interface of technological, economic, social and policy aspects of the liberalization process in electricity sectors. Thus the scope is not bound by a single discipline and has the ambition to reflect on the multidisciplinary aspects of electricity sectors as encompassed by policy analysis. The motivation behind the choice of a multidisciplinary approach stems from the fact that the nature of the issues themselves appears to be multidisciplinary.

The addressed domain constitutes a framework in which various actors including regulators, public and private enterprizes and consumers play a role. The interests and actions of each actor affect the others, which creates an interplay among the actors. This interplay lies at the heart of the scope of this research.

Within the liberalization framework, the functionality of the electricity system must be safeguarded while the private and public enterprizes strive for their respective financial and strategic goals. The critical task of safeguarding the security of the technical system is currently undertaken by entities that are called Transmission System Operators (TSO), which are typically independent governmental entities in electricity sectors.

The security and sustainability of the system depends on various operational, tactical and strategic moves of the stakeholders (consumers as well as the private and public entities such as generators, retailers and system operators). While private entities strive to safeguard their financial and strategic interests, consumers expect low cost and reliable electricity without any black-outs as in California in 2001 (Woo, 2001). The system operator is responsible for the coordination of electricity transmission and system reliability.

The competitive and cooperative relationships of these entities determine game situations at various levels (i.e., operational, tactical and strategic) in electricity markets. The strategic relationships between the aforementioned actors in the electricity system constitute the main scope of the research. The following two chapters draw an overarching framework for the theoretical basis and the research methodology used in various relevant cases.

1.5 Overview of this thesis

Three parts characterize the organization of this thesis as depicted in Figure 1.1.

The first part sets the context of the thesis by providing a background. After Introduction, which has provided a brief background, demonstrated the targeted scientific/knowledge gap and proposed a method, Chapter 2 provides elaborate background information regarding the electricity markets, liberalization process and strategic behavior. Chapter 2 is followed by Chapter 3, the theoretical background of the study. This chapter presents interrelation among systems thinking, policy analysis and game theory. Thereafter Chapter 4, the chapter on the design of this research, demonstrates how the methodology is applied to the problem.

The second part of the thesis is the main body and contains three cases that compose the crux of this research. In each of these cases a strategic issue is presented and a game theoretical model is formulated. The effect of liberalization on load-shifting incentives is examined in Chapter 5. Chapter 6 looks at the congestion problem in transmission system as the subject. Financial transmission rights, which is a congestion management mechanism, is examined. The last case chapter, Chapter 7 deals with a broader topic, i.e., innovation in electricity sectors. Boosting innovation in electricity sectors has been one of the goals of liberalization process. This chapter examines the effect of liberalization on innovation in electricity sectors.

Finally, the third part of the research offers reflections and conclusions, in which the policy synthesis from the cases and consulted expert opinions are gathered together and scientific reflections on the practice of the research are made. Chapter 8 wraps up the policy implications of the cases and provides a policy synthesis. This chapter also presents some reflections on the game theoretical formal modeling and positions it with respect to similar modeling approaches. Conclusions and future research considerations are presented in Chapter 9.

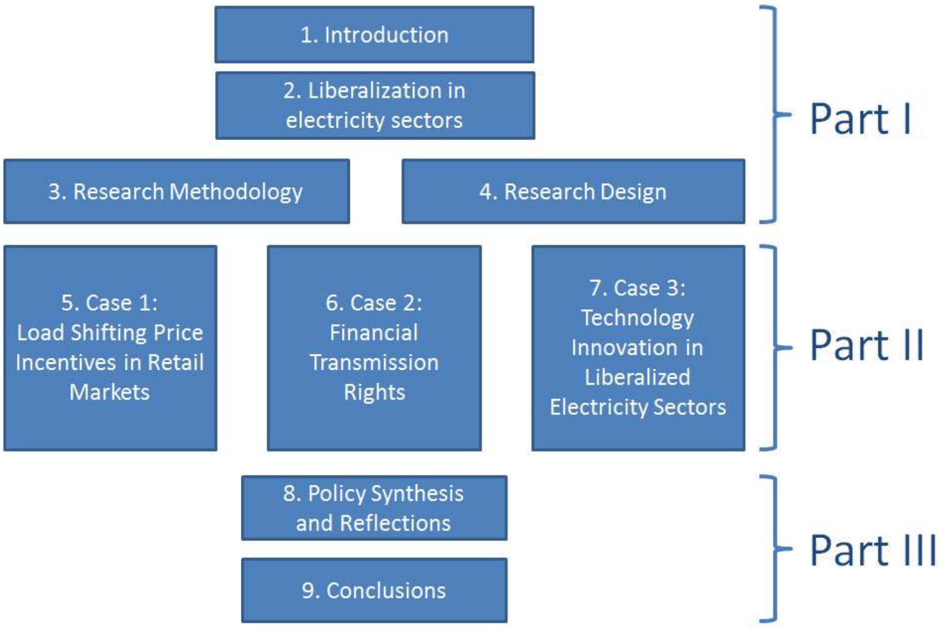

Figure 1.1: Overview of this thesis

Chapter 2

Liberalization in electricity sectors

2.1 Introduction

In the first chapter, an introduction to the thesis is made. The subject and the scope of the research, as well as the scientific gap that is driving it are described. Moreover, the research methodology is explained briefly, which is to be further explained in Chapter 3. This chapter aims to explore and frame the application domain of the research. Liberalized electricity sectors and associated policy problems related to strategic behavior are further articulated. What is the liberalization process in electricity sectors and what is its historical background? How can one characterize electricity sectors with respect to the emerging liberalization? How does liberalization affect electricity sectors? What are some examples of potential strategic behavior that arise from this setting? In this chapter, the aim is to explicate the background of the problem by answering these questions.

At this point it is appropriate to clarify that the models in this research deal with the liberalized markets at steady state rather than dealing with the the transition process. Thus the transition dynamics regarding liberalization are not directly the subject of this study. Nevertheless, since the policy discussions based on the models are related to the ongoing process of liberalization and discussions regarding reregulation of the markets are still actual, the liberalization process is also examined briefly in this chapter.

A brief overview of the liberalization of public sectors, specifically of the networked industries, is provided since the electricity sector reform is a natural consequence of a wider liberalization paradigm shift. The drivers of liberalization, especially in the context of the European Union, are highlighted. Furthermore, electricity sectors are characterized in relation to the liberalization process, showing how current policy problems that are subjects of this thesis have arisen. Finally, the necessity of regulation in the transition period from regulated to liberalized electricity markets is underlined.

2.2 Concepts of liberalization: Deregulation, reregulation, privatization, corporatization

Various terms are used casually with respect to the liberalization process in the scientific literature and media. The meanings sometimes overlap and sometimes refer to completely different concepts. To continue the discussion without any ambiguities in meaning, these terms are clarified in this section.

The dictionary meaning of the word ‘liberalization’ is the act of making rules or laws more liberal or freer. In an economics sense, liberalization means opening up the market for new entrants, creating competition and thus freedom of choice for consumers. It is debatable whether liberalization directly implies competition or not. Armstrong and Sappington (2006) distinguish liberalization policies as being pro-competitive or anti-competitive. According to this point of view not all rule changes made for liberalization end up increasing competition. In the context of this thesis, the term ‘liberalization’ refers to all attempts by policymakers – changes in rules, laws and incentive mechanisms – to open up the sector to more participants than the status quo. Thus by using the adjective ‘liberalized’, an object that is subjected to policy changes of liberalization is referred. These policy changes include the deregulation of the networked industries as well as the reregulation of them.

The rationale behind ‘deregulation’ is that fewer and simpler regulations would lead to a raised level of competitiveness, and therefore a higher productivity, more efficiency and lower prices overall. Although deregulating a market can be satisfactory in conventional industries, in networked industries other regulatory mechanisms might be required. Collectively these new mechanisms constitute the reregulation of networked industries (Künneke and Finger, 2007). In the literature, the term ‘deregulation’ usually has the same meaning as ‘dereglementation’, which means the abolishment of the rules. Deregulation is interpreted in this thesis as changing the rules such that the market becomes open to economic actors to compete, i.e., creating a market. However, contrary to the connotation of the word, this does not necessarily mean less rules in the sector.

In networked infrastructures, ‘reregulation’ usually follows deregulation. Change in rules triggers institutional evolution. In essence, all the sectors that go through liberalization transit from preventive, static, monopolistic government control to corrective, transparent, information-based, dynamic and interactive control. The liberalized markets are subject to the rules of new institutions. In most cases, direct legal and governmental control is replaced in exchange for indirect control.

Initial considerations about what trajectory the regulation would have during transition to liberalized markets were different than what we think now, in the middle of this transition. Initially, according to the ideal view of deregulation, regulatory intensity would increase during the transition phase. During the transition phase the regulator would get the market running by introducing some preventive rules, which would, for example, prevent incumbents from using their market power resulting from their historical monopoly position, unbundle the incumbents, safeguard quality and so on. Once the transition was over and the competition was on track, regulation was expected to become less intense and the market would become deregulated, as depicted in Figure 2.1 (Bergman and Vaitilingam, 1998).

However, this view has been questioned ever since right after the beginning of the lib-

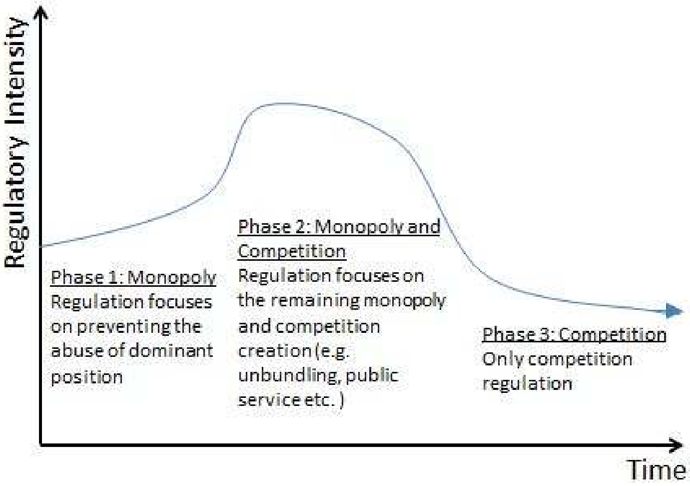

Figure 2.1: Expected regulatory intensity during liberalization process

eralization process, as policymakers have realized the difficulties of safeguarding critical technical functionalities of the infrastructures and providing the accustomed quality. Thus the manifestation of reregulation in the form of large numbers of new rules and regulations has become quite dominant and is likely to remain so in the future. Although at first glance they seem to be the same concepts, deregulation and liberalization have different meanings and refer to different concepts. Liberalization does not necessarily carry fewer rules, whereas the very definition of deregulation involves fewer rules. ‘Deregulation’ is underlined by various scholars (Heuvelhof et al., 2009; Vogel, 1996; Wubben and Hulsink, 2003) as a suitable term to describe the regulation intensity track, whereas ‘liberalization’ is what is called the transition to open markets. In fact, the unexpected increase in regulatory intensity is recognized in the literature as the ‘reregulation paradox’ (Bergman and Vaitilingam, 1998).

Two other widely mentioned concepts related to the liberalization are ‘privatization’ and ‘corporatization’. Although liberalization and privatization are seen by many as the same concept, theoretically they are quite different. Liberalization has the aim of freeing up the market from monopolies to allow for competition, as described above. Unbundling of the incumbent state owned monopolies is usually the first step in the effort of creating competitive markets. In the electricity sector this phenomenon has taken the form of the uncoupling of generation facilities, retail service providers, transmission system operators and distribution system operators. Naturally these entities should be owned or controlled by different actors rather than the political authority. Thus the entities are either privatized or corporatized. Corporatization is the process of transforming a governmental entity into an autonomous and independent corporate identity and legal position. However the resultant corporation is still owned by the government. On the other hand, with privatization, as the name suggests, the economic entity is owned by a private person or party. In Europe corporatization together with unbundling has generally occurred as a first step to liberalization in the public sector and networked infrastructures.

2.3 Liberalization in public sector and networked infrastructures

Liberalization can have a broad connotation, depending on the context of the discussion. It often refers to fewer government regulations and restrictions in the economy in exchange for greater participation of private enterprises. For developed countries, in order to remain globally competitive, liberalization means partial or full privatization of government institutions and assets and fewer restrictions on domestic and foreign capital, goods and labor. This view of economic liberalization is framed as a positive participative economic model in the developed Western world. Former British Prime Minister Tony Blair stated, regarding the liberalization discussions in the UK and Europe, that "Success will go to those companies and countries which are swift to adapt, slow to complain, open and willing to change. The task of modern governments is to ensure that our countries can rise to this challenge." (Blair, 2006). In his talk, Blair continuously referred to the GDP rise in some developing countries such as China and India and points out that Europe lags behind in the GDP race, seeing liberalization as the key to coping with global competition among firms and nations alike.

On the other hand, for some if not all developing countries, liberalization might have a rather negative connotation, referring to opening up their economies to foreign capital and the privatization of national assets in general. The World Trade Organization (WTO), which steers the regulation of the rules of trade between nations at a global level, has been the driving institution behind the penetration of liberalization in developing countries. While encouragement of economic reform in developing countries is among the aims of the WTO (Matsushita et al., 2006), is harshly criticized, especially regarding the practical implementations of the respective economic reforms. Khor (2000), the former director of the Third World Network,[1] points out that the win-win image of the liberalization process in the developing countries is not correct by definition in his talk at the World Economic Forum in Davos titled *Rethinking Liberalization and Reforming the WTO*. Pointing out the post-liberalization reports such as *Trade and Development Report* issued by UNCTAD (1999) in 1999, he exemplifies the increase in trade deficits in third world countries and the decrease of GDP growth in the 1990s as compared to the 1970s. The immaturity of the third world economies for global competition is shown as the main reason for this negative trend in developing nations. From the perspective of the sovereign third world nations, it is highlighted that it is of utmost importance to make the necessary regulations for a healthy market before opening up the borders to foreign trade. Similar studies have proven that there is no automatic correlation between liberalization and growth.

Even for well developed economies with competitive companies, there are various pitfalls on the way to liberalization. Especially where networked infrastructures are concerned, these pitfalls are evident. In order to illustrate poor liberalization, one may consider the privatization of a national monopoly without unbundling and expecting competitors to enter the market. This mode of liberalization does not provide a good archetype for liberalization. Just as no layperson would jump into the boxing ring against a professional boxer, no company is able to compete against an ex-monopoly. Lowering the barrier of entry, which

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[1] *Third World Network* is a network of individuals and organizations that conducts research on a wide range of issues related to the third world countries.

is a theoretical must for perfect competition, should be a goal of a healthy liberalization recipe. Unbundling national monopolies before privatization is the archetypal policy action that aims for a competitiveness boost of the respective market (Stoft, 2002).

The capital intensiveness of large infrastructures creates economies of scale for the initial provider of such infrastructures and poses a barrier of entry for other enterprises and associated infrastructures. This leads to natural monopolies, which is justified by the capital intensiveness of the sector and sometimes by the operational infeasibility of creating competing infrastructures. Historically these natural monopolies have been owned by the state in European context and regulated private enterprises in US. The main difference between networked infrastructures and the other conventional sectors is that networked infrastructures operate on costly, usually spatially dispersed, bulky infrastructures. Especially in networked infrastructures, such as electricity, gas, water, telecommunication and postal sectors, the natural monopoly characteristic are commonly observed. Although many other conventional markets began to become liberalized much earlier in the Western world, networked infrastructures remained under the control of government agencies up until the 1970s mostly due to the argument of natural monopoly.

As far as the networked infrastructures are concerned, liberalization is an unfolding global process which has gained acceleration during the post Cold War period. Towards the end of the 20th century, economists observed that some aspects of the public sector such as productivity, customer orientation, efficiency and prices, were lagging behind the liberal sectors. Another lagging aspect was ‘innovation’, which is investigated in Chapter 7 of this thesis. The absence of competition is blamed as the source of such problems. The end of the 1970s saw the first liberalization attempts in the US, whereas in the UK, liberalization started only at the beginning of the 1980s. Not long after, it found its place on the desk of the European Commission as a major task to be dealt with. Since then Europe has kept itself busy with this ongoing experimentation. For the last two decades networked infrastructures comprising telecommunications, air transport, postal services, electricity, gas, water and rail transport – all of which have historically been state monopolies – have been laid on the operating table for an implementation of liberalization.

The main driving theory behind the attempts of implementing competition into the networked infrastructures is that of industry structure and the accompanying concept of ‘contestable market’ (Baumol, 1986). The contestable market idea argues that for competition to exist in infrastructure, one does not need to implement competing infrastructures. Instead of competing **with** new infrastructure, enterprises compete **for** the already existing infrastructure. Exclusive rights to use the infrastructure can be sold on a market in which enterprises compete. Transmission rights in electricity markets, as an example of such a market, is examined in Chapter 6.

2.4 Drivers of liberalization in Europe

Liberalization in European electricity markets is a natural result of a more general trend of liberalization in Europe. In turn liberalization in Europe succeeds considerable national liberalization efforts in UK, Chile and New Zealand in the 1980s and early 1990s, resulting in a unique, transnational, systematic character unlike its predecessors. Once strong governmental institutions and various providers of goods and services have been transformed through the pursuit of liberalization. But what were the reasons for such an immense transformation? Why did Europe feel the urge to transform its critical public sectors into competitive markets? Although these questions are not at the center of this study, some discussion regarding the drivers of liberalization is appropriate in order to frame this research.

Two categories of drivers for liberalization in Europe are internal and external drivers. There are two main internal drivers behind liberalization from a European perspective. One of these drivers is the weakening competitive power of Europe with respect to the US and China. The economic integration of Europe with its well-integrated infrastructures has a very important role in resurrecting the economic power of Europe. The creation of an internal market is also another important expected outcome from the transnational European liberalization process. This would also be effective in strengthening the economic power of Europe. In general, liberalization is considered a tool for rendering Europe more competitive.

Another implicit yet important objective behind liberalization is to unite Europe and weaken political fragmentation. Weakening national monopolies would result in weakening national interest, which tends to create stalemates due to the high degree of political fragmentation in Europe. In fact, post-war politics and the idea of creating a united Europe have always had the objective of safeguarding peace. In 1943, when Jean Monnet became a member of the National Liberation Committee, the free French government in Algiers, he addressed the Committee:

> “There will be no peace in Europe if the States rebuild themselves on the basis of national sovereignty, with its implications of prestige politics and economic protection (...). The countries of Europe are not strong enough individually to be able to guarantee prosperity and social development for their peoples. The States of Europe must therefore form a federation or a European entity that would make them into a common economic unit (Fontaine, 1988).”

Globalization which has been the dominant trend for the past three decades, with its spread of neo-liberal ideology all over the world, has been the main external push for liberalization in Europe. The ideology has been leading to pressure for less regulation and more privatization. Ever increasing technological capabilities, such as the increasing role of ICT in commerce and culture, crete a further push for liberalization. This is observable not only in the form of free markets but also in the public policies and organizations governed by the new public management (NPM) theory of public governance (Hood, 1991). According to NPM, a more decentralized public sector is envisioned. This vision of public governance brings about markets, managers and performance metrics into governance, which means a more competition- and results-oriented public sector that treats citizens as shareholders or customers, is exposed to market dynamics transparent to the public and behaves in accordance with the incentive schemes (Ferlie, 1996).

As an example of government corporations that have emerged since liberalization, one can refer to the transmission system operators (TSOs) in electricity markets. In an electricity market, the TSO, which is the responsible entity for transporting energy using the electricity infrastructure, is generally a company that is not under the direct control of government but is owned by the government. TSOs have their own budgets and financial targets and are judged based on their financial performance, just like any other for-profit organization. TSOs can be considered a result of NPM theory in the sense that they are considered to be

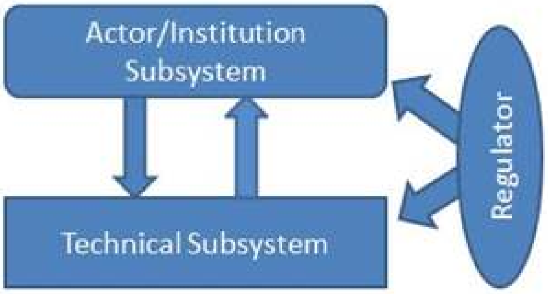

Figure 2.2: Electricity sector as a socio-technical system

government companies rather than government agencies.

The general purpose of this study is not to make a cost benefit analysis of the liberalization in the electricity sectors. Assessing the transition dynamics with respect to the European liberalization process is also not in the interest of the study. Rather this research examines the strategic behavior of the market participants in liberalized electricity sectors in steady state. The game theoretical formal models, which will be examined in Chapters 5, 6 and 7, are based on established liberalized electricity markets. These markets are sometimes contrasted to the monopolistic counterparts, which represent the pre-liberalization era. In the next two sections, pre and post-liberalization electricity sectors are discussed.

2.5 Electricity sector before the reform

In essence, the electricity sector is a socio-technical system, as depicted in Figure 2.2. The technical subsystem is operated by actors/institutions and, depending on the regime, the regulator regulates the whole system either by providing right incentives or by directly intervening. In centralist regimes, the regulator assumes the role of all the actors operating in the system, which means that a monopolistic government organization controls the technical subsystem at every stage in its supply chain, from generation to retailing. In more liberal regimes the institutional subsystem is composed of several independent actors and even private entities. The holy grail of the liberalization process is distributing the roles among independent actors such that a competitive, self-regulating market is created. Although this final goal ideally aspires to there being as little regulator intervention as possible, experience so far has shown that regulation has always been required for the smooth operation of networked infrastructures.

Classically, the whole electricity system is operated by the vertically integrated national or regional monopolies, as depicted in Figure 2.3. Being in control of the operation of the entire value chain, from generation, transmission and distribution to retailing, the monopoly is able to optimize the resources and the technical processes. The integral monopoly used to be justified by the fact that the sector was a natural monopoly because of the sole infrastructure, which limited the competitive aspect of the sector as well as the complexity of the system. High investment risks, advantages of economies of scale, technical integrity and indivisibility have also been counted as points to justify national monopolies.

The transformation in the electricity sector generally occurs in multiple phases. The first step of restructuring involves the unbundling of production, transmission, distribution and supply operations. The second step is to form a competitive market that involves wholesale market and retail competition. This market ideally is open and easy for new entrants to operate, enabling benefits from perfect competition in both the production and supply sectors. The third step in this transition period is to establish an independent regulator. This regulator is responsible for incentive regulation of transmission and distribution networks. The final step of reform is to privatize the existing publicly owned businesses (Jamasb and Pollitt, 2005).

The whole purpose of the industry is to provide a public service; electricity in this case. In the past, investment decisions were made centrally according to economic development plans, and capacity expansion was created accordingly. Economically, the sector involves large investments in transmission, distribution and production, accompanied by low marginal production costs. The vertical integration of the company kept the critical technical functionalities of the system safeguarded in an optimal manner, which was another argument in favor of monopolies.

Remarkably, the process of liberalization brought about change for all activities in the value chain in various infra-structural sectors, including customer relations, perspectives on technology, ownership and governmental relationships, and the electricity sector was not an exception.

2.6 Electricity sector after the reform

The new paradigm in the electricity sector manifests itself especially at the institutional level. Initially, the transformation towards a unified market was envisaged as being composed of multiple steps (Jamasb et al., 2005). The first step of restructuring involved the unbundling of the utilities into smaller corporations, each of which were responsible for production, transmission, distribution and retailing operations. This would create different markets in different parts of the electricity value chain.

The second step would be to make the markets competitive and allow third parties to enter into competition with the incumbent in production and later in retailing. Although, in theory, the successor companies do not have to be private organizations, in practice these

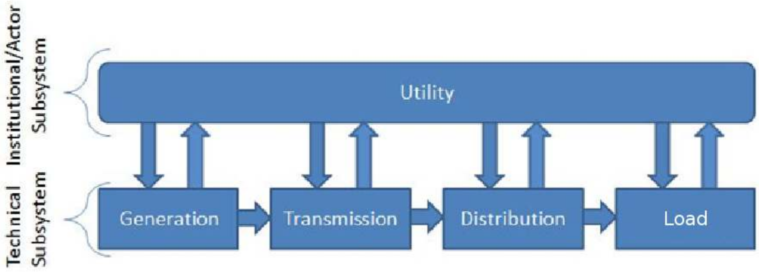

Figure 2.3: Electricity sector before reform: Old Paradigm

companies have been just that most of the time. Resulting markets would ideally be open and easy for new entrants to enter, enabling benefit from competition in both the production and the supply segments of the value chain.

The third step in this transition would be to establish an independent regulator. This regulator would be responsible for the regulation of transmission and distribution networks. in general terms the resulting electricity sector can be described as in Figure 2.4.

The electricity production segment of the value chain is generally liberalized to some extent but not to a satisfactory level. In most countries there are not more than three main production companies,[2] one of which usually holds more than 50% of market share as seen in Table 2.1. The market concentration still leaves room for market power abuse. However, with increasing renewable energy inflow, new players are likely to emerge.

On the boundary between electricity generation and retailing, economic arrangements occur on the institutional level. Historically these arrangements have been long-term bilateral contracts, the role of which is filled by power exchanges. Both bilateral contracts and short-term market mechanisms are still in play, and each have respective merits.

Yet on the institutional level another market is formed between retailer firms and consumers. These involve short-term contracts with small consumers and longer contracts with large consumers. In some cases large consumers may hook up to the system on higher voltage levels, thereby passing retailers and buying directly from the producers through bilateral contracts.

Other important actors arising from the liberalization process are system operators and managers. Transmission and distribution systems have remained natural monopolies, since building parallel infrastructures have often proven to be both costly and redundant. These infrastructures are managed by their corresponding monopolies. Transmission system operators (TSOs) are, in general, independent government corporations. These corporations are responsible for the transportation of electricity using the electricity infrastructures, i.e., the electricity grid.

In parallel to the transition from the old paradigm to the new paradigm, distributed gen-

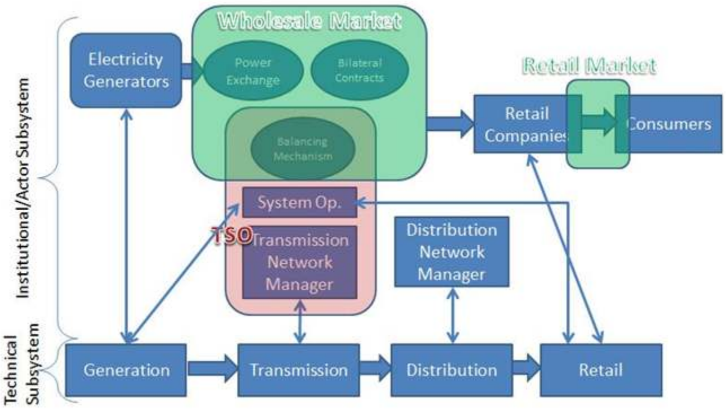

Figure 2.4: Electricity sector after the reform: New Paradigm

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[2] Companies are considered as main if they produce at least 5% of the national net electricity production.

	2003	2004	2005	2006	2007	2008	2009	2010
Austria	7	5	4	4	4	4	4	4
Belgium	2	2	2	2	2	2	2	3
Bulgaria	5	5	5	5	5	5	4	5
Czech Republic	1	1	1	1	1	1	1	1
Denmark	2	3	3	2	2	2	2	2
Germany	4	4	4	4	4	4	4	4
Estonia	2	1	1	2	1	1	1	1
Spain	5	5	4	4	3	3	4	4
France	1	1	1	1	1	1	1	1
Italy	4	4	4	5	5	5	4	5
Cyprus	1	1	1	1	1	1	1	1
Latvia	1	1	1	1	2	2	1	1
Lithuania	2	2	3	4	4	4	3	5
Luxembourg	1	1	2	2	2	2	2	2
Hungary	6	4	3	4	5	6	3	3
Malta	1	1	1	1	1	1	1	1
Netherlands	4	4	5	5	4	4	4	5
Poland	7	5	5	5	5	5	5	5
Portugal	3	3	3	3	3	3	3	2
Romania	7	6	7	7	7	7	6	6
Slovenia	3	2	2	2	2	2	2	2
Slovakia	1	1	1	2	2	2	1	1
Finland	4	5	4	5	5	5	5	4
Sweden	3	3	3	3	3	3	3	5
United Kingdom	6	7	7	6	7	9	8	8

Table 2.1: Number of main electricity producers (Eurostat, 2012)

eration is an emerging feature of electricity sectors. New renewable technologies such as wind energy and photovoltaics make it technologically feasible to produce in smaller quantities in dispersed locations. Various private entities and individuals termed ‘prosumers’ are able to produce the electricity that they consume at least partially with such new technologies. The amounts of energy produced might exceed prosumers’ actual consumption in some situations. Feed-in tariffs, which enable prosumers to sell their excess energy back to the grid, is a new application in electricity sectors and reflected in the paradigm shift from a monopolistic to a multi-actor electricity sector. As a group, prosumers are certainly emerging as another actor in the new paradigm in electricity sectors.

2.7 Market power in electricity markets

Market power describes the ability of an actor to alter the market price of a good or service. As far as market power is concerned, transmission rights are considered important by practitioners as well as theorists. The Federal Energy Regulatory Commission (FERC) of the United States recognizes two sources of market power, one due to insufficient demand-side response and the other due to the transmission constraints (Commission et al., 2002b). Three types of market structures are often examined in the literature on market power (Nanduri and Das, 2009). These are monopoly, oligopoly and perfectly competitive markets. The incumbent neoclassical economics school hypothesizes that the shift from monopolistic markets to perfectly competitive markets boosts social welfare. Thus the main motivation behind the deregulation of the electricity markets is to increase competition in pursuit of social welfare.

The market economy was put in place to allocate resources in a more efficient way compared to the pre-liberalization period and to maximize the welfare of both consumers and producers. Thus the purpose of the market mechanism is not only to enhance the welfare of producers but also of consumers. However, in its canonical examples, market power increases the welfare of producer, who have the market power, and decreases the welfare of consumers as well as global welfare. Excess profit as a result of market power is considered a signal of inefficiency and market failure. Hence, market power mitigation is among the prime concerns of electricity market designers and policymakers. Different policy alternatives that relate to market power concerns are readily available in the literature (Mount, 2001; Nanduri and Das, 2009; Twomey et al., 2006; Weiss, 2002). Oligopolistic models are one of the most powerful tools to reveal market power since they explicitly incorporate structural, behavioral and market design factors (Twomey et al., 2006). These types of models, such as the Cournot oligopoly model or Bertrand competition model, can be effectively addressed by game theory (Cunningham et al., 2002; Vickers, 1985; Vives, 1984).

Market power mitigation involves counteracting the power of key actors to price and supply electricity. Market power emerges from size as well as network position (Lusan et al., 1999). The efficiency considerations regarding oligopolistic markets have been well studied with the use of models (Acemoglu and Ozdaglar, 2007; Allaz and Vila, 1993; Fershtman and Judd, 1987). Typically, these models demonstrate that a low number of market participants causes market power and rent-taking risks. Oligopolistic markets are not strategy-proof, since they enable incentives to collude for price fixing. Some scholars claim that even monopolies may be better than oligopolies in terms of efficiency (De Fraja and Delbono, 1989). A common argument for this perspective relates to the following argument in favor of the concept of natural monopoly: certain public goods achieve higher economies of scale when produced by a single supplier. This opinion is further reinforced by the reasoning that governments usually regulate monopolies to keep prices low whereas in an oligopolistic market with tacit collusion high monopoly prices can be produced behind the façade of competition.

In the context of electricity markets, the idealized market setting for perfect competition has yet to be achieved; most deregulated electricity markets actually converge to oligopolistic markets. However, oligopolistic markets are prone to market power issues resulting from the presence of large, dominant firms. To date, oligopolistic markets, have prevailed in Europe. In the UK, Germany, France and Spain, more than 70% of the market is dominated by only two generation companies (Boisseleau and de Vries, 2010).

Table 2.1 shows the historical numbers of main electricity generators in EU electricity markets (Bosch et al., 2007; Goerten and Ganea, 2009). It can be observed that the most prominent countries in Europe have few, if not single, generation companies. This shows how far away the ideal of a perfect market is and supports the idea that oligopolistic models are well-suited for the examination of market power. Also, the oligopolistic characteristics of electricity markets have long been theoretically investigated. Hobbs is a pioneer of this branch with his network models of spatial oligopoly (Hobbs et al., 2001). In his analysis he uses the Bertrand model, taking spatial differences into account. One other important remark derived from this table is that although restructuring has been slowly put into place for more than a decade in Europe, its implementation remains incomplete.

The Herfindahl Hirschman Index (HHI) is the conventional measure of market power in market power analysis. HHI is derived through a simple arithmetic based on the percentages of the market shares of the market players. The sum of the squares of the market shares gives the HHI of the market. Effectively, HHI results in a number between 0 and $10,000$, with 0 indicating a perfect market and 10000 a monopoly. However, in the context of electricity markets, HHI is considered by several scholars (Blumsack et al., 2002; Borenstein and Bushnell, 1998; Hogan, 1997) to be inappropriate, as it neglects the special properties of electricity, including the presence of network structure, instantaneous market clearing and congestion limits. Alternative methods such as the ‘pivotal supplier method’ are seen as more suitable in the context of electricity markets (Blumsack and Lave, 2003; Helman, 2006).

Along the lines of market power discussions, the 2000 California black-out stands out as a significant experience. The crisis was initiated by electricity suppliers, which deliberately decreased electricity supply, raising the price in order to gain higher margins (Weare, 2003; Woo, 2001; Woo et al., 2003). Borenstein et al. (1999a) and Joskow and Kahn (2001) argue that in the summer of 2000, for many hours, electricity prices exceeded competitive prices, which hints at a significant market power abuse. Although at the time of the crisis the HHI of California was 664, which was below the limit (1800) as set by the FERC and below many comparable power markets, California failed as a competitive market (Blumsack et al., 2002).

Theoretical studies of transmission rights also show that market power is a significant component to be evaluated in electricity market design (Chandley, 2002; Gilbert et al., 2004, 2002; Joskow and Tirole, 2000; Leautier, 2001). Formal modeling and simulation has been utilized by researchers since the very beginning of the restructuring and liberalization of electricity markets. Some characteristics of electricity markets, such as being oligopolistic, are classical subjects of microeconomics literature. Additionally, various modeling studies taking electricity markets as their subject matter have been developed. Models have proven to be critical tools for supporting policymaking and corporate decision-making in this regard. Learning by doing in the electricity grid can be prohibitively expensive. Thus, strategy models are a valuable source of policy learning.

In addition to those mentioned above, various modeling approaches can be found in the literature in this context (Hobbs et al., 2001; Hogan, 1992; Kamat and Oren, 2004). For instance, Joskow and Tirole (2000) studied radial line topography with respect to generation and transmission rights. They show that generators in a power exporting region can levy their monopoly situation to game the market. This result is in line with transmission congestion literature (Borenstein et al., 1997, 1999b; Bushnell and Wolak, 2000; Chao and Peck, 1996), which states that generators are likely to levy their market power for self-benefit. Over-utilization of key portions of an electricity grid results in the problem of congestion, from which market players can benefit. Efforts to mitigate the congestion problem in electricity transmission systems have led to various congestion management approaches (Bompard et al., 2003; Chao et al., 2000; Fang and David, 1999; Kumar et al., 2005; Oruç and Cunningham, 2011; Ruff, 1999; Singh et al., 1998; Zhang et al., 2003). These are discussed in detail in Chapter 6.

2.8 Strategy-prone complexities of electricity markets

The institutional changes in electricity sectors induced by the liberalization process add various institutional complexities to the electricity industry. In addition to the institutional complexities,various technical complexities exist that have to be taken into account when exploring strategic behavior in the electricity sector. Safeguarding the critical technical functions in the electricity sector has utmost priority. The generation of electricity and the demanded load has to be balanced at all times, due the physical constraints of electricity. Thus, unlike conventional markets, electricity markets are always cleared (Künneke and Finger, 2007). Moreover, the active control of the flow of electricity is difficult because of the physics of electricity. According to Kirchoff's laws, electricity flows through the transmission lines based on the least resistance on the lines. The flow cannot be directed deliberately and the electricity flows through various parallel paths, forming an equilibrium. This phenomenon is widely referred to in the electric power transmission literature as 'loop flows' (Bialek, 1998; Cardell et al., 1997; Chao and Peck, 1996; Chao et al., 2000; Hogan, 1992). A sudden disruption of the equilibrium of electricity flow in a stable electricity system, for example due to a disruption on a transmission line, can jeopardize the whole system since a new equilibrium of electricity flow might cause the overloading of some other transmission lines. The cascading failure of transmission lines can cause persistent black-outs (Crucitti et al., 2004). Hence a set of critical technical functions has to be safeguarded for the security of the physical system. These critical technical functions can be categorized in three categories, namely: capacity management, interconnection and interoperability (Finger et al., 2005; Hirst and Council, 1997).

One particular challenge is storing electricity, a problem which durable goods producers and suppliers do not face (Künneke and Finger, 2007). By nature, the storage of electricity is limited. Furthermore, demand and supply can be highly volatile. For instance, during large social events there can be greater than usual demand locally, which in turn may disturb the daily supply routine considerably. This results in system management challenges for the transmission system operators (TSOs) (Künneke and Finger, 2007; Oruç and Cunningham, 2011; Sugianto and Lu, 2002).

When a mismatch exists between supply and demand, generators are sped up or slowed down by means of frequency control (Kundur et al., 1994). Although this technique compensate for a gap between supply and demand to some extent, usually additional generation capacity is required since the frequency has to be kept within a certain range in accordance with the electricity line specifications. As for electricity capacity storage, electricity systems benefit from technologies such as pumped-storage hydroelectricity generation, as this can provide storage functionality by consuming power during off-peak hours and feeding it back to the grid during peak hours (De Fraja and Delbono, 1989). However, their usage is limited due to the need for expensive investments in addition to environmental and political costs.

Both the technical and institutional complexities in networked infrastructures and specifically in electricity sectors lead to various new opportunities for strategic behavior. One may even regard the increasing number of active independent parties as a potential threat in terms of strategic behavior. The institutional changes induce new market mechanisms which might not always be strategy-proof. By strategy-proofness, it is meant that a market mechanism in which no player has any incentive to behave strategically in this context.

Although all markets are prone to strategic behavior, the extra complexities of electricity sectors give rise to a higher inclination toward adverse strategic behavior. In a conventional market, an incumbent player might leverage its market power to game the prices for its own benefit. The Californian electricity crisis, which was caused by a flawed market design, is a canonical example of the results of such behavior in electricity sectors. Furthermore, the above mentioned technical and institutional complexities of the electricity industry form a greater potential for strategic behavior.

In contrast to conventional markets, the invisible hand of the market does not always work smoothly in electricity sectors. Experience has so far shown that even more regulation than previously anticipated may be needed for the sake of the healthy operation of the electricity markets. Some severe problems that showed up after the liberalization process can be listed as, among others, high price volatility, network instability, under-investment in capacity and infrastructure, a lack of innovation investments, a lack of network integration and market concentration, latter of which leads to considerable market power abuse (Newbery, 2002).

The Electricity Directive 96/92/EC (Commission et al., 1996) and Gas Directive 98/30/EC (Commission et al., 1998) were announced by the European Commission in 1996 and 1998, respectively, as the first directives to liberalize the European electricity and gas sectors. After these two directives were released, as a reaction to the academic studies that drew attention to some unsatisfactory points, the Commission amended them (Bergman and Vaitilingam, 1999). The main changes were the requirement of regulated third party access for both gas and electricity and the requirement for all countries to establish independent regulators to approve transport tariffs *ex-ante* and to monitor and report to the commission on the state of the markets, especially on the supply-demand balance. Clearly the Californian electricity crisis triggered some fears on the European side of the Atlantic. The high prices triggered by strategic behavior in the Californian market demonstrated how crucial the continuity of electricity supply is and how costly scarcity can be for the public.

Furthermore, Newbery (2002) draws three conditions for liberalization, based on the experiences of the European and American electricity sectors. The first condition states that, for a competitive wholesale market, potential suppliers must have access to the transmission grid in order to reach the customers. This view scraps the Single Buyer Model, where the transmission operator buys as monopoly and sells to the customer. This condition underlines the ownership separation of transmission from generation.

The second condition underlines the requirement for sufficient and secure supply at all times. This imnplies the necessity of a reliable and adequate networked infrastructure, adequate generation capacity and sufficient supply of primary fuels such as gas, oil, coal or uranium.

The third condition is appropriate regulation of these liberalized utilities. The first two conditions are recognized by the Commission. However, perhaps due to the vagueness of it, this third condition has been largely ignored by the Commission. Newbery (2002) states that without these conditions, there are serious risks that the benefits of liberalization would be lost and political support would be harmed, due to flawed outcomes of the reform process. Newbery (2002) also explains the possible problems of access, capacity, contracting and market power in EU electricity markets.

2.9 Summary

In this chapter, the background of the problem that motivates this study is presented. The chapter starts with the concept of liberalization and explains its in the context of electricity sectors. Along these lines, the role of regulation within the liberalization paradigm is highlighted. Furthermore, what liberalization means for the public sector is explained. Some motivations behind the liberalization process are discussed.

Later the chapter focuses on the electricity sector and compares the pre- and post-liberalization periods of the electricity sector. Some institutional complexities that have arisen since liberalization are highlighted. How these institutional complexities, together with the technical complexities of the sector, reinforce the strategic behavior is explained. Finally, the regulation within the liberalization paradigm is underlined, drawing from evidence from the first years of the liberalization process and from some other academic studies.

The next two chapters elaborate on the methodology employed in this research. Chapter 3 draws a theoretical frame of the approach to the problem and relates it to a wider research paradigm of modeling studies and operations research. Chapter 4 states the methodological choice of this thesis and explains how the research is conducted. After these two chapters, three cases and thought experiments follow which exemplify some specific problems associated with strategic behavior in liberalized electricity markets.

Chapter 3

Research Methodology

3.1 Introduction

In the previous chapter, the subject of this thesis is introduced and some background information regarding the subject matter is discussed. The liberalization of electricity sectors, which results in multiple independent actors and strategic interactions between these actors, is described. It is emphasized that the liberalization process adds institutional complexity to the sectors, which were already quite complicated technically. The increased complexity is underlined as a breeding ground for adverse strategic behavior, which might not always be easy to understand without meticulous scientific analysis. The primary purpose of this research is defined as understanding potential strategic behavior in liberalized electricity sectors by using game theoretical formal modeling.

Having defined the aim of the research, in this chapter the research methodology of this study and the associated literature are specified. In an effort to provide the theoretical background of our research, the literature on which our approach is built on is presented as well. Our theoretical framework stems from systems analysis, operations research, policy analysis and game theory. The interrelation of these disciplines is akin to systems thinking, which is further elaborated in Section 3.2. Furthermore, systems thinking in a multi-actor context is emphasized. From multi-actor systems thinking, game theoretic perspective is deducted. Correspondingly, the motivation behind the choice to use formal modeling, in particular game theoretical formal modeling, as the method of inquiry is explained.

In addition to the goal of explaining the research methodology and the motivation behind it, the second goal of this chapter is to make interconnections between various separately evolving yet closely related interdisciplinary fields, i.e., systems theory, policy analysis and game theory. Although the relationships among these fields are neither a mystery nor unheard of, an account for the idea of utilizing game theory with systems thinking is presented in this chapter. It is beneficial to address this point by emphasizing the legacy of these fields on game theory and present the interconnections that led to the analytical framework of this study.

3.2 Systems thinking

The term system is derived from the Greek word *systema*, which literally means composition and refers to a whole composed of interacting subparts or components. It is a term that has been embedded in human thinking probably since Aristotle who asserted: “The whole is greater than the sum of its parts”. However, since the second world war it has developed a more specific meaning in various intellectual fields such as in science, philosophy, technology and politics.

Components or elements, which can be identified as individual entities, constitute the system. The relationships between these elements constitute a structure. The relationships and processes among these interconnected elements determine the behavior of the system. The elements, structure, inter-connectivity and behavior of a particular system are the subjects of systems theory, which aims to elucidate the principles that all systems adhere to. Systems theory analyzes the issue at hand as a whole that is comprised of interacting parts. Upon identifying the issue and defining the purpose of an analysis of a particular system, system analysts define a system boundary, which draws a hypothetical border between the system elements that are relevant to the issue and their surroundings. Afterwards, making simplified representations of the system, which are called models, and testing various hypotheses using these models is one method to understand the issue.

Systems science shows itself in various disciplines, thus it can be identified as a glue for interdisciplinary research. It covers formal sciences such as biology, mathematics and physics as well as their respective applications such as control theory, operations research, cybernetics, social systems theory, systems engineering, systems psychology, etc. Even systems philosophy, which proposes that understanding a problem can be accomplished only by understanding the individual parts of the problem (Capra, 1997), can be included in this line. Taking a holistic view of the problem or the phenomenon is the fundamental intersection of these common system approaches in various disciplines.

The second world war and post-war period saw the rise of systems thinking. This development comes as no surprise if one observes the ever-increasing number of different technologies and their interactions. System thinking was born as a reorientation of these technologies for their efficient utilization. Post-war developments paved the way to a number of fields such as information theory, game and decision theory, cybernetics, systems engineering and operations research, all of which are akin to systems thinking. The intersection point of these fields is the effort to combine different technologies into a coherent whole. As such, holism prevails over reductionism in this period. Ackoff (1973) even describes the post-war period as the systems age and acknowledges a transition from the machine age to the systems age. New technologies of the post-industrial revolution period converged and formed systems of technologies. Efficient coordination of these systems has become increasingly more important. Operations research has prevailed as a distinct and recognized discipline since this transformation of scientific perspective.

3.2.1 Operations research, optimization and linear programming

It is well known in the literature that operations research, both as a term and as a recognized discipline, first came into existence before World War II (Kirby, 2003; Larnder, 1984; Waddington, 1973). The efforts to develope new radar technologies and investigate the efficient usage of those technologies drew radar scientists into issues of overall system design, operating procedures and tactics. These research efforts were seen as highly beneficial and, when war broke out, a small team of scientists performed as the world's first operations research (OR) team.

Optimization is at the core of OR. Optimization is, in essence, a very narrow action that necessitates a clear and well-defined problem formulation. Mathematical optimization is the process of selecting the best element from some constrained or unconstrained set of available elements.

Operations research has extensively utilized optimization techniques in the dawn of the discipline. Decision making with optimization techniques can be stated as being the backbone of the discipline. It is even possible to say that during its early periods, OR was unthinkable without optimization. However, during the post-war period, this notion has relaxed. Later in the second half of the 20th century, the categorization of soft OR and hard OR emerged as described by Checkland (1999). With regard to this split, the work of Simon (1955, 1997) is a typical example of hard OR, whereas 'System Dynamics' of Forrester (1961, 1971a) and 'Limits to Growth' of Meadows et al. (1992) exemplify soft OR that instead aims to achieve insight.

The evolution of optimization that has resulted in the OR that is known today began with linear programming. Linear programming arose as a mathematical technique to optimize cost and return planning during World War II. Dantzig (1951), with his simplex method, is accredited as one of the most influential mathematical scientists in this regard. The simplex method is a mathematical procedure for determining the best outcome in a given mathematical model, reduces the number of possible optimal solutions to be checked and provides computational efficiency. Dantzig (1963)'s *Linear Programming and Extensions* book was published in 1963 and became one of the seminal books of the field.

George Dantzig joined the mathematics section of the RAND Corporation in 1952. The RAND Corporation is credited as a pioneer of policy think tanks that utilize mathematical methods for real-life problems. The successes of the RAND corporation in utilizing mathematics and rational thinking in decision making and planning increased the importance of these techniques. If one assumes a mental model of science, in which a particular intellectual framework drives a method to become an application, at this stage of the history of systems science, operations research (OR) was motivated by a rather static framework that utilizes a somewhat static method, i.e., linear programming and optimization, with fairly well-defined problems.

Around the same time that Dantzig invented his simplex method, John von Neumann developed the duality principle. The duality principle shows that an optimization problem can be viewed from two different perspectives, i.e., the primal problem and the dual problem. The solutions of two different perspectives do not always reach the same result, and therefore a duality gap occurs. The duality principle can also lead to the formulation of a linear complementarity problem (Cottle et al., 2009), which is equivalent to computing a Nash equilibrium in a bimatrix game (Cottle and Dantzig, 1968). Thus, metaphorically, the dual problem landmarks a transition from a mono-variable 'optimization' paradigm to multi-variable 'equilibrium' paradigm. In reality, game theory, a multi-variable, multi-actor and thus multi-perspective view of optimization, had already begun to appear in the literature. Von Neumann (1928) had already published his paper *Zur Theorie der Gesellschaftsspiele* and later his seminal book *Theory of Games and Economic Behavior* (Von Neumann and

Morgenstern, 1947) by this time.

Game theory and its place in systems thinking is discussed more broadly in Section 3.4. Moreover, in Appendix A and in (Oruç and Cunningham, 2014), the relationships between optimization and game theory are discussed in depth.

3.2.2 Policy analysis

In the age of speed that we live in, circumstances such as technologies, political positions and people's demands change rapidly. Even the natural trends, such as the atmospheric temperature increase, have accelerated in the 21^{st} century, mainly due to the accelerated contribution of catalyzers such as the increase in greenhouse gas emissions due to growing human activity. Change means uncertainty. In these uncertain times, policymakers' decision making tasks have become more and more troublesome. Especially long-term policies can bring about far-reaching consequences that the policymakers have the responsibility to take into account. Policy analysis comes into this gloomy picture to help policymakers make the right decisions.

In this thesis by policy analysis especially *ex-ante* policy analysis is emphasized, as opposed to *ex-post* policy analysis. *Ex-ante* policy analysis refers to policy development efforts. The orientation of this type of study is always towards future. As a result of this forward-looking orientation, *ex-ante* policy analysis always incorporates methods that specify and estimate behavioral models and uses these models to assess the consequences of alternative policies. On the other hand, policy analysis can also refer to *ex-post* analyses, which are applied after a policy is implemented and usually uses methods that depend on the data and observations that stem from the results of the policy intervention. Our policy analysis viewpoint, which is the *ex-ante* approach, does not rule out the experiences gathered from the past experimentations.

Fragmentation exists along various dimensions in the policy analysis discipline, in addition to the *ex-ante*, *ex-post* split (Thissen and Walker, 2013). It is a multidisciplinary field that employs various scientific methods from different scientific disciplines, such as linear programming from operations research, agent-based modeling from computer science and Q-methodology from psychology. In addition to its richness of applied tools and methods, the problem domain of policy analysis is almost ubiquitous spanning all publicly relevant decisions governments and authorities make. This versatility, fed by a wide spectrum of tools and methods, naturally results in various styles and schools of policy analysis. Some policy analysts are independent researchers, whereas many others are political advisers. This fragmented picture of the field, due to the sense of a lack of cohesion and unity, triggers the question of whether the field exists as such (Mayer et al., 2004).

It is possible to talk about qualitative and quantitative policy analysis, i.e., policy analysis which depends on mathematical and computational rigor vs. rhetorical, lexical analysis. Another split involves the focus of the analysis. Some policy studies emphasize the process of policy making, such as whether it is participatory or not, the roles of the actors, etc., whereas some authors analyze only some given policy options and explore the pros and cons of each against the other. Some of these approaches do not contain models but conduct evidence-based analyses, such as, a cost-benefit analysis. 'Policy analysis' label is adopted by various kinds of research approaches, and therefore the diversity of policy analysis approaches are abundant.

Although, on first impression, policy analysis seems to be too dispersed for a coherent discipline, the perspective for the policy analysis discipline is not as grim as it may seem. Much common ground characterizes the field, such as its goal orientation. Most, if not all, policy analysts would agree on the point that the policy problem drives the method in policy analysis. Policy analysts address the problem and make an appropriate choice regarding the set of methods they will use (Walker, 2000). The treatment of the issue at hand can employ different approaches, depending on the specific school of thought of policy analysis. The multi-dimensional natural of the field is also characteristic to policy analysis. A policy analyst should typically have a pragmatist character with respect to the choice of methods and techniques.

3.2.3 Multi-actor systems and actor analysis

Policy analysis arose on the back of OR methods and tools in the post-war period. It has proven to be useful, eventhough it was applied in limited range of circumstances among the wide spectrum of policy problems. It was criticized by policy practitioners as being much too rationalistic and focusing too narrowly on static policy means, thus being unsuitable for application to a wide range of policy problems. Hard OR techniques, which aim to optimize variables for a fixed problem formulation, could not be used for many policy problems that also involved power struggles, personal relations, strategic behavior etc. Soon it was understood that policy analysis could not be constrained to a narrow scope.

Policy processes became recognized as being predominantly the social processes of and between actors, and policy analysis was required to expand beyond decision analysis of narrowly determined, fixed policy problems to include the analysis of actors, i.e., actor analysis (Hermans and Thissen, 2009). This reality does not downplay the importance of the hard OR techniques and methods that developed during and after World War II. Hard OR-based policy analysis has been useful in decision making and does still deal with some assumptions about policy mechanisms. Moreover, it has provided an appropriate basis for actor and policy analysis in general.

Since the development of soft OR methods and the transformation of political regimes throughout the world, which manifested itself in the decentralization of decision making and political authority, policy analysis has been equipped with the theories of actors. The importance of individual actors, actor networks and actor systems has continually increased. Various actor-focused approaches are introduced into policy analysis. Hermans and Thissen (2009) define four theoretical dimensions that characterize actor analyses, namely networks, perceptions, values and resources, and classify actor analysis methods into these dimensions. Networks emphasizes the stable connections of the actors with each other whereas resources refer to the things that the actors are in control of and in which they have interest. Perceptions and values emerges as two interlinked dimensions which are based on the actors' evaluations of the situation. Perceptions refer to the views of how things operate in a give situation and what the causal relations are, whereas values refer to actors' subjective evaluations of the situation based on their norms, interests and purposes.

3.3 Formal modeling as an inquiry method

The ultimate goal of science is to understand and control real-life situations whenever possible. Providing an account of whether this are possible or not is also a duty of science itself. It should be noted that the majority of real-life phenomena is difficult to understand, let alone to control. With the progress of scientific methods, science constantly challenges this assumption and opens a horizon of possibilities for scientific inquiry. As the theories and concepts to describe real-life phenomena develop, so does our comprehension of human kind.

This thesis recognizes modeling as a tool in this endeavor. Modeling may have different meanings in different contexts. However, the common denominator of all the definitions is that a model is a simplified representation of an object, system or phenomenon. Rothenberg (1989) describes a model as "a representation of some referent object that can yield an answer to a question about this referent object more efficiently than the referent object itself". Rothenberg's description implies that modeling is a tool for analyzing and understanding a phenomenon.

Abstraction of a real world phenomenon into a model involves the simplification of the phenomenon. Without abstraction, which metaphorically means cutting the real-life phenomenon into bits and pieces and grasping it accordingly, comprehension is highly difficult, if not impossible. J.W. Forrester necessitates the use of models in understanding the real-life phenomena with the following words (Forrester, 1971b):

> "The image of the world around us, which we carry in our head, is just a model. Nobody in his head imagines all the world, government or country. He has only selected concepts, and relationships between them, and uses those to represent the real system."

The level of abstraction of a model is an important design decision that a modeler has to make. The amount of complexity that a model includes to represent a particular real-life phenomenon determines level of abstraction. The higher the level, the less detailed the model is. The highest level of abstraction represents the entire real-life phenomenon as one component. In comparison, the lowest level represents literally all of the components of the system in the model.

Different levels of system complexity require different levels of abstraction. In a relatively low-complexity system, such as a home heating system, the level of abstraction could be low and yet may involve many parameters, such as ambient temperature, external temperature, setting point and possibly a delay component. Even at this low level of complexity, it might require various assumptions such as the isolation factor of the environment or the dissipation of heat to comprehend and model the system.

Compared to low-level abstraction, high-level abstraction involves many more assumptions but has the ability to model more complex systems. The choices of the assumptions become more and more crucial as the abstraction level increases. The assumption choices are encompassed by what question the decision maker poses. In case of socio-technical systems where lots of complexities kick in, making appropriate assumptions has the utmost importance.

In this thesis, formal models are utilized, which are the mathematically expressible models, as opposed to conceptual models, which are expressible verbally. Formal models, as well as mental models, serve the purpose of abstracting real-life phenomena to a level that can be comprehensible to the human mind.

Models are meant to be used as tools for understanding the real-life phenomena that they represent. The modeler models real-life phenomena to be able to test some hypothesis or to answer some modeling questions. Answering modeling questions is the functionality of the model, along with serving the purpose of understanding. The modeler must bear in mind the assumptions and known and unknown uncertainties throughout the analysis.

In general, the use of formal models opens up a large range of tools for deductive thinking and the deepening of knowledge about socio-technical systems. Out of many prominent results of formal models, two can be mentioned within this context. Arrow's impossibility theorem implies that when voters have more than two distinct options, no voting system can convert ranked individual preferences into a collective ranking while also meeting a specific set of criteria. These are laid down in (Arrow, 1950). Arrow's impossibility theorem showcases one particular case where social processes can be thought of in terms of formal models. Without Arrow's formal model, we would not have discovered that our informal ideas about some of our democratic principles are logically inconsistent.

Another example is Axelrod and Hamilton (1981)'s iterated prisoner's dilemma tournaments that deemed the simple strategy of tit-for-tat, which says "do good for those who do a favor for you and punish those who harm you", as a socially successful strategy. Axelrod's tournament sets up a fictitious world in which 'self-interest at the expense of the benefit of others' appears at first glance to be the most rewarding strategy. However the tournament, in which different strategies programmed by various academics and students compete with each other on a prisoners dilemma game iteratively, showed that the tit-for-tat strategy, which represents reciprocal altruism, can prevail even in an environment in which self-interest is the sole source of payoff. The results of the tournament inspired scholars in understanding the evolution of cooperation and altruism (Axelrod and Hamilton, 1981; Axelrod, 1997; Fosco and Mengel, 2011; Phelps et al., 2011). Axelrod's results showed that in a very simple game, socially favorable behaviors, such as being nice to the nice individuals or promoting mutual interest, simply for the purpose of survival or self-interest.

3.4 Game theoretical formal modeling

Game theory began, to appear in science history during the late 1940s and 1950s through mathematics and economics, particularly with the seminal book *Theory of Games and Economic Behavior* by Von Neumann and Morgenstern (1947). Soon after, it was embraced by a wide range of disciplines including biology, operational research, political science, experimental economics and so on.

Essentially, game theory is the study of rational decision making in the context of situations in which two or more participants have choices to make and the outcome depends on the choices made by each. Nobel laureate game theorist Robert Aumann (2002) stressed the interdisciplinary nature of game theory with the following words:

> "There are very few subjects that have such a broad, interdisciplinary sweep. Let me just put over here some of the ordinary disciplines that are involved in game theory. We have mathematics, computer science, economics, biology,

> (national) political science, international relations, social psychology, management, business, accounting, law, philosophy, statistics."

The multidisciplinary nature of game theory fits well with our philosophy of drawing from various disciplines and related theories and shedding light on policy problems, which in general have and inherent multidisciplinary nature.

In the next subsections the game theory literature is explored in conjunction with different contexts, i.e., policy analysis and electricity market modeling, which underline this research. Then we discuss the suitability and limitations of game theory. Finally game theoretical formal models are positioned in comparison to the other modeling methods used in electricity market modeling.

This section and Chapter 3 in general have been written to discuss the methodology in conjunction with the other methodologies in the literature and to attempt to position game theoretical formal modeling in relation to its peers. For the details of the applied methodology, readers may refer to Chapter 4, where the research design and applied methodology are described elaborately.

3.4.1 Game theory in the context of policy analysis

The use of game theory in policy science goes back at least to the Cuban nuclear weapon crisis between the US and the USSR. Basically, the concept of assured mutual destruction kept the countries civil to each other. Everyone has nuclear weapons and nobody wants to make the first strike due to fears of retaliation. Game theorists, such as Schelling et al. (1985), made significant contributions to the growing literature on modern war and diplomacy. They supported the idea that the nuclear weapons were only useful as deterrents, using game theoretical models.

Policy analysis, in our view, has wide connotations and can refer to 'analysis' in a general sense to imply the use of various disciplines and tools to achieve insights into "not only the examination of policy by decomposition into its components but also the design and synthesis of new alternatives" (Quade, 1982). This view of policy analysis embraces our envisaged method to employ game theory together with formal mathematical models that describe both the technical and social aspects of the socio-technical system to be examined. Our policy analysis understanding includes the aim of extracting policy-relevant information and insights from the issue at hand but not limited to it. We draw from the understanding that "the aims of policy analysis extend the production of facts; policy analysts seek also to produce information about values and preferable courses of action. Policy analysis therefore includes policy evaluation as well as policy recommendation" (Dunn, 2003).

In positioning our game theoretical approach inside the quasi-discipline of policy analysis, the hexagon model described by Mayer et al. (2004) is considered. The approach of this research is in relation to the 'research and analyze' and 'advise strategically' corners of the hexagon model and employ rational style as described. A rational policy analysis approach is employed in this research. Rationalist policy aims to achieve maximum social gain; that is, governments should choose policies their result in gains to society which exceed costs by the greatest amount, and governments should refrain from policies if costs are not exceeded by gains (Dye, 1975).

The 'research and analyze' type of policy analysis comprises "a form of applied research that uses research methods and techniques that are scientific or derived from science, such as surveys, interviews, statistical analysis but also simulation and extrapolation" (Mayer et al., 2004). Translation of the outcomes of this research type to policies or recommendations is not the primary part of the mission. It is up to the political system to make decisions.

On the other hand, the 'advise strategically' type of policy analysis takes the case as a strategic activity and tries to safeguard the client's interests within the described strategic arena. The policy analyst advises the client on the most effective strategy to achieve the goals, given the situation and the likely counter-moves of the opponents.

Game theory can be considered as an intermediary between these types with respect to its rational and scientific attitude toward modeling the issues and considering the strategic behavior of the actors other than the policymaker.

3.4.2 Positioning game theory in electricity market modeling

There exist various modeling techniques to model electricity markets. These techniques can be grouped into system-focused modeling techniques such as computational general equilibrium (CGE) models or linear/non-linear programming (LP/NLP) models and actor-focused modeling techniques such as agent-based modeling (ABM) or game theory (GT). This categorization depends on the initial focus and the initial purpose of the modeling technique. System-focused modeling techniques emphasize the mechanics of the system and base the modeling on the mechanics. For example, in CGE and LP/NLP models, market equilibrium is the focus and is the primary situation modeled. On the other hand, in actor-focused modeling techniques, actor behavior is the focus of the modeling. The modeling effort is based on actor behavior and is expanded to system mechanics. In ABM and GT, the actor behavior is the departure point of the modeling effort. Whether it is system-focused or actor-focused, an energy system model always possesses both actor and systems perspectives. In essence, both of these categories are systems models. However, actor emphasis naturally predominates systems emphasis when the actor behavior is under scrutiny in actor-focused models and vice versa. Acknowledging the usefulness of differing models techniques, our choice of game theory with respect to the alternative approaches is motivated in this section.

Many of the economic energy modeling draw from the neoclassical economic theory and are based on partial and general equilibrium models. The game theoretic perspective has common ground with partial equilibrium models, as both emphasize the self-interest of the individuals and search for an equilibrium. More generally, game theory examines the decision interactions of multiple competing or cooperating individuals intending to reach their own targets. Game theory investigates the strategic actions, cooperations and market power of individuals and coalitions.

Computational general equilibrium (CGE) models are the basis of most of the system-focused economic energy models. As described above, CGE draws from the equilibrium of supply and demand relations, profit maximization under a free market with perfect competition, low-threshold and optimal allocation, and the distribution of resources. The dynamics of CGE are driven by capital accumulation and the exogenous growth of production factors and productivity. CGE models produce equilibria of all markets according to the economic behavior of individual agents.

In order to take into account not only economic but also environmental and climatic concerns, energy models have recently integrated ecological, ecosystem, and climatic aspects as well as the economic aspects. Stylized climatic interrelations are developed into CGE models that incorporate contemporary climate and energy systems. These models are usually referred to as ‘integrated assessment models’ (IAM). Costs of climate change are predominantly assessed through IAMs that incorporate the physical relations of climate change and the economic effects of damage functions. Multidisciplinary approaches are predominant in integrated assessment models, which aim to provide a comprehensive evaluation of the climate change impacts (Weyant et al., 1996).

The MARKet ALlocation model (MARKAL) is another prominent energy model that is widely used in economic environmental energy modeling communities. It is a linear programming (LP) model with some nonlinear programming (NLP) variations (Fishbone and Abilock, 1981). The energy system details represented in MARKAL include primary energy resource supplies, energy conversion technologies, end-use demands and the technology options that can be used to satisfy the specified demands. The MARKAL model deals with general energy-related questions such as those related to the energy mix and the price trends of energy resources.

As opposed to the above -isted system-focused modeling techniques, an actor-focused modeling technique is embraced in this study. Game theoretical formal modeling deals with the actions of the individuals and examines the competition and cooperation between them. As explained in the previous chapter, by definition, game theory possess an actor-centered view. Various examples of game theoretical studies that analyze the strategic behavior of individuals can be found in the literature (Ferrero et al., 1997; Gintis, 2000; Hobbs et al., 2000; Rubinstein, 1989; Singh, 1999).

In addition to game theoretical formal modeling, another promising and emerging field that is worth attention is agent based modeling (ABM) in the category of actor-focused modeling techniques. ABM is a moderately young research paradigm that offers methods for modeling electricity markets. It is possible to say that ABM is a product of increasing computational power and object-oriented programming practices. These models usually have a high level of detail and low level of abstraction. In some cases, literally every relationship among the actors is modeled, thanks to the growing computational power of modern computers. A growing number of researchers have developed agent-based models for simulating electricity markets. Diverse approaches among the ABM modelers can be observed. Weidlich and Veit (2008) provide a critical survey of such diverse ABM models applied to electricity wholesale markets.

According to Hourcade et al. (1996), economic energy modeling techniques can be classified into bottom-up and top-down models. Agent based models are a typical example of what he calls a bottom-up approach, as the complex modeling of most, if not all, elements in the system are conceptualized in these models. On the other hand, game theory is described as a top-down approach according to this classification (Hourcade et al., 1996). The classical game theoretical models, which analyze the system, make too many assumptions to be able to calculate an equilibrium mathematically instead of low-level detailed modeling.

The electricity market is different than conventional markets as elaborated in Chapters 1 and 2. The characteristics of the electricity sector push most classical modeling methods, including classical game theory, to their limits. Some equilibrium models such as CGE either do not consider strategic behavior or assume that players are completely rational and have complete information. Also, they are blamed for not referring to daily learning effects (Rothkopf, 1999), which game theory can address (see Chapter 6). Furthermore, Weidlich and Veit (2008) claim that game theoretical analysis is limited to stylized trading situations among few actors with unrealistic behavioral assumptions. However in this research, the usefulness of the game theoretical formal modeling approach is examined in understanding strategic behavior in the context of several cases, which are studied in Chapters 5, 6 and 7.

The system-focused modeling methods that are derived from CGE and LP/NLP have different perspectives than those of game theory and ABM. Because of the actor-focused approach of both game theoretical formal modeling and ABM as well as the utilization of numerical and computational methods, these two modeling techniques are considered as akin to each other. Gintis (2000) even considers ABM as "computer programs that use game theory to create artificial strategic actors, set up the structure of their interactions and their payoffs, and display and/or record the dynamics of the ensuing social order." Indeed, one can encounters many cases in which ABM and game theory mix with each other. However, the point that distinguishes these two modeling techniques is related to the way they showcase strategic behavior and abstraction level, on other words, the level of detail that these modeling methods exhibit.

3.4.3 Suitability and limitations of game theory in this research

Game theoretical models are meant to model strategic relationships between various stakeholders in general. The purpose of this type of models in this research is to do the same in the electricity markets in order to answer some strategy-relevant questions. The source of such strategic questions are the strategic relationships between the actors in the field. These strategic relationships manifest themselves in terms of either cooperation or competition, for each of which a rich library of concepts has been developed in the game theory literature.

Different problems have different strategic aspects that can be addressed by different subfields of game theory. For example, non-cooperative game theory is a suitable approach for addressing the issues caused by the price wars between electricity retailers, whereas the problem of tacit collusion in the capacity expansion problem can be better handled by using cooperative game theory more suitably.

Each of the cases of this study deal with self-interested independent actors and their strategic relationships with each other. Moreover the actors in focus are private companies, which line up to the rationality assumption of game theory to a large extent. The load-shifting case in Chapter 5 deals with the decisions of various retailers who have entered the market as a result of liberalization. The case looks at the effect of the change in price incentives for load-shifting. Clearly the actors are self-interested and can be considered as rational. The second case in Chapter 6 examines the behavior of generation companies within an electricity and financial transmission rights market. In this case, too, the actors are self-interested and can be considered rational. Finally, the innovation case in Chapter 7 examines generation companies that decide to invest in the research and development of their generation technologies. The actors are in this case are again generation companies who are self-interested. Hence, a non-cooperative game theoretical perspective fits well with these cases since rationality and self-interest assumptions are suitable in all of them.

Although from many perspectives, game theory is the approach that best suits our aim of shedding light on liberalization-related issues of electricity sectors with respect to strategic behavior, there are many points that concern the applicability of game theory in general policy analysis settings. These issues arise due to the general characteristics of game theoretical modeling. Below three main reasons why a policy analyst should be careful about when using game theory are listed.

First of all, rationality is an important assumption that makes game theory vulnerable to criticism. From some experiments with the prisoner's dilemma it is known that the narrow, self-regarding perspective is not realistic. Already in the beginning of the prisoner's dilemma research in psychology, it was shown that in a 100-round iterative prisoner's dilemma game, even highly qualified players make their decisions based on emotional considerations such as a feeling of revenge or through surprising cooperation (Rapoport and Chammah, 1965).

A second important assumption that is predominant in game theory is that of information ownership. Information is always an important aspect of games, as is the assumption that whoever has information should be taken care of. Players estimate their payoffs according to the information that they have about the situation. If players are only partially informed about the game, their decisions can be catastrophic for themselves. For this reason information assumptions are to be watched out carefully.

A third point to be careful about when using game theory in policy analysis is the long-term behavior among the players. The games formulated in the literature usually conceptualize short term relations of the players. However, in reality these players usually have long-term relationships with each other. Companies may seem to behave irrationally when only a short-term game is considered, but in reality they may anticipate social constraints, moral codes of conduct, business ethics and so on, as they are in long-term relationships with the other actors. Additionally they may have other relationships that are not conceptualized in the game. Hence, all in all, the modeler should be aware that game theory models can only help to understand a limited part of the whole picture.

Furthermore, in relation to the neoclassical roots of the game theoretical models, the criticisms of neoclassical economics are applicable as well. It is possible to track normative biases of neoclassical economics in game theoretical models that describe an ideal world view instead of focusing on actual economy. The 'homo-economicus' of neoclassical economy exists in game theoretical models when these models conceptualize the behavior of actors at an aggregated level. Moreover, like neoclassical models, game theoretical models are criticized for being too much focused on mathematics rather than on reality. These are valid criticisms of game theoretical models and should be kept in mind while analyzing the outcomes of these models. These limitations diminish the knowledge claims derived from game theoretical models.

Since game theoretical modeling always tends to frame the situation according to a particular case, the resulting insight might not be generalizable without overlooking the assumptions being made. Usually the policy analyst faces a trade-off between mathematical rigor and proximity to reality and tunes the modeling assumptions accordingly. The policy analyst should be careful when referring to the reality based on the results of the model. All the limitations of game theory, both those that are listed and those that might possibly arise during the course of the research, will be addressed with careful consideration and discussed in retrospect in Chapter 8.

3.5 Summary

In this chapter several goals are met. First, the literature that drives this study is referenced. The methodological framework is developed and positioned in the literature of systems thinking and operations research. The evolution of the field from the technique of optimization through to the idea of actor analysis is shown.

Policy analysis and game theory are related to a brief history of systems thinking. Hard OR techniques such as optimization and linear programming are related to the rapid development of game theory. Soft OR and policy analysis are described as having been born from a response to a practical gap of policy practitioners. Furthermore actor analysis and the field of multi-actor systems are underlined as natural results of changing political contexts and developing needs for policy analysis. Game theoretical modeling is proposed as a methodology that has characteristics both of the hard and soft OR domain.

Additionally, formal modeling is motivated as an inquiry method in this chapter. Modeling is defined as a representation of the real-world system and advocated as an inexpensive and effective method to test hypotheses in comparison to experimenting on the real system. Furthermore, some prominent examples of modeling studies are provided from the literature.

Game theoretical formal modeling is further highlighted as the choice of methodology for this study. A brief history of game theory is provided. Additionally, the position of game theory in the contexts of policy analysis and electricity market modeling are eplained. Limitations of the game theoretical formal modeling in policy analysis and positioning game theory in electricity market modeling approaches in the literature finalized the chapter.

The next chapter presents the design of this research based on the methodology and literature presented in this chapter. Explaining how the research proceeds at the operational level, Chapter 4 is a binding chapter that guides the rest of the research. Subsequently, Chapter 4 is followed by there cases, in which the research plan is actually executed.

Chapter 4

Research Design

4.1 Introduction

In the previous chapter, methodological background of the study was presented. A brief historical account of the evolution of systems thinking, which is embraced in this study, was provided. This chapter presents how the methodology is applied to the specified field, while drawing from the theoretical account provided in the previous chapter, by answering the following question: How exactly is the methodological choice translated into practice?

The chapter begins with motivating the choice of game theoretical formal modeling and explaining the type of game theory to be applied in this thesis. Next, the choice of cases and though experiments are motivated and explained. Subsequently, how exactly game theoretical models are applied with cases and thought experiments is explained. Finally, the policy synthesis chapter of this thesis is motivated.

4.2 Game theoretical formal modeling in electricity sectors: Exemplifying theory

Since the ongoing liberalization process in electricity sectors and its consequences are related to various actors with different interests and behaviors, game theory is a natural choice, owing to the fact that it deals with competition and cooperation among multiple actors. There have been various studies that have utilized game theory in analyzing electrical systems, the most prominent of which can be seen in (Hobbs, 1986; Hogan, 1992; Singh et al., 1998; Stoft, 1997). These models are seldom utilized inside a policy analytic framework, and they usually aim to reproduce real-life behavior mathematically or computationally. The original models of this thesis draws from these game theoretical models in the literature. The models in the literature are considered and reframed to create exemplifying models, which are easier to comprehend. Based on these models corrective solutions for real-life problems are discussed. Utilizing these approaches in a policy analysis framework, namely aiming to enrich the understanding of policymakers and suggesting solutions, is a relatively novel field of study. More elaboration of the research conduct can be found in Chapter 4.

Our approach to game theoretical modeling starts with basic assumptions about the utility functions, production functions or cost functions of the actors in the model akin to neoclassical thinking. These simple functions cumulatively resulted in aggregated behavior. Accepting the assumptions, the outcomes of the model were the result of the functional relationships of the assumptions. Both the behavior of the simple functions and the behavior of the aggregated behavior were tested by means of sanity checks.

This modeling technique, which emphasizes clear basic assumptions and not complicated mechanisms, is described as ‘no-fat modeling’ by Rasmusen (2007) or ‘exemplifying theory’ by Fisher (1989). The main point of the approach is to figure out the simplest assumptions to generate interesting, counterintuitive results that provide insights into the subject matter. Fisher (1989) says “Exemplifying theory does not tell us what must happen. Rather it tells us what may happen”. Predictions can be made about future events, but usually the main motivation is to explain and understand rather than predict.

Although the style boasts simplicity, a certain amount of formalism and mathematics is needed to ground the ideas of the modeler. Thus, exemplifying theory requires a middle step between mathematical abstraction and non-mathematical vagueness. Although, advocates from both worlds would find the exemplifying theory narrow, one must beware of the calls for rich and complex models. Richness in the model often causes the model to be too incomprehensible or incoherent to be applied in real situations. According to Rasmusen (2007), “richness in a model tends to make it flabby”.

For communication purposes, it is important to explain the basic assumptions of the model. Thus, the description of the basic assumptions must be clear and easy to comprehend. If the assumptions are not clear for the audience, the counterintuitive results of the model will not be credible. The perceived ‘loose’ assumptions are accounted for.

4.3 Cases and thought experiments: game theoretical formal modeling in action

Strategic behavior manifests itself in various embodiments in liberalized electricity sectors. In Chapter 2, the institutional transition of the electricity sector is discussed and in Figure 2.6 various market formations, which are the results of liberalization transitions, are shown. These markets are pivotal in understanding potential adverse strategic behavior since they are the arenas of actor interactions of the reformed industry.

Since strategic behavior has different embodiments in different parts of liberalized electricity sectors, three cases were chosen to analyze strategic behavior.

The criteria for the choices of the cases are listed as follows:

- Potential Strategic Behavior: The cases should contain some potential strategic behavior by the market participants. This implies that there should be more than one market player and there should be a conflict interest or alignment of interests.
- Scale: The case we describe should be suitable for small-scale, stylized, comprehensible game theoretical modeling.
- Policy Relevance: The cases should be relevant to some policy problems, since the purpose of this study to derive policy-relevant insights into potential strategic behavior.

- Diversity: The cases should be diverse to cover different facets of the liberalization process. Both the retail market and the wholesale market should be covered by separate cases.

The first and the second cases were chosen from the retail and wholesale markets, respectively. The third case touches upon a broader subject, i.e., innovation, in the electricity sector. For each case, background information and the prior studies concerning the cases are provided, which are followed by original game theoretical formal models, each of which is tailored towards the specifics of the respective case. Thought experiments are considered using these models.

The first case analyzes the impact of price incentives for load-shifting in liberalized retail electricity sectors. The large-scale change in the regulatory regime meant a shift from the monopolistic electricity retailer market to an oligopolistic market in the electricity retail market. This process resulted in some concerns over the impact of abatements that are paid by the retailers to the consumer for them to shift their load from day-time to night-time. A free-rider effect is observed in this setting, which is further discussed in Chapter 5. Load-shifting was chosen as the subject matter of this chapter, as it is a relatively overlooked area and has the potential to demonstrate some of the effects of liberalization in the retail electricity market.

The second case takes congestion management as its subject, which is a hot topic concerning strategic behavior in liberalized electricity wholesale market. Chapter 6 specifically analyzes financial transmission rights (FTR), which is a congestion management technique. A thought experiment in which information withholding can give a strong advantage to a player is demonstrated. FTRs and congestion management are chosen as the subject of this chapter, as these topics are emerging topics in the European context and *ex-ante* analysis of this new mechanism is thus a contribution to the literature.

Finally the third case investigates the problem of innovation in electricity sectors. Lack of innovation, being one of the arguments of the liberalization movement, is evidently sustained as an issue in liberalized electricity markets. In Chapter 7 a game theoretical model is formulated to analyze the dilemma of the lack of innovation in liberalized electricity sectors.

After determining the cases, some potential strategic behavior of the actors were thought through. Accordingly, the markets and strategic interactions of the actors were modeled. The modeling cycle is explained in detail in the next section.

The models created were recursively tested and developed according to the real-life expectations of the model outcomes. After the completion of the models, some scenarios or thought experiments were conducted. Hypotheses are formulated and tested using the created models. These thought experiments would induce an overall understanding of strategic behavior in the context of the described cases.

For each case the applied modeling cycle and policy argumentation process is described in the next section.

4.4 Modeling cycle and policy argumentation

Modeling requires a meticulous and iterative effort. Continuous trial and errors and revisions are necessary in many cases. The modeling methodology of this study is described as a continuous cycle. The modeling cycle accommodates some phases that swing from the real world that is observed in the physical environment to the conceptual world constructed in the mind.

Figure 4.1 depicts the employed modeling cycle in this thesis. In most modeling practices there is always a reality gap between the model and the real world phenomenon. The modeling effort starts with observation but does not finish with the modeling and testing stage. Policy recommendations are devised from the modeling work, which should ultimately be linked to the real-world problem. A more elaborate explanation of the modeling cycle is made in the following subsections.

4.4.1 Observation and actor analysis

Typically the modeling work begins by observation of the real-world phenomenon that is under examination. Actor analysis naturally follows this observation stage in the actor-focused modeling approach in this thesis. The interests and typical preferences of the actors drive the relationships between multiple actors and the underlying technical, economical, and social system. The actors and their actions are interdependent. In some cases, cooperation of the actors is required to safeguard sustainable operation for the good of all the players. In other cases competition between the actors serves the best interest of all the actors. The relationships between different actors as well as the economic, technical and social mechanisms drive the building of the game theoretical model. The interdependencies of the actors are determined by applying actor analysis. Actor analysis is a precondition for game theoretical formal modeling of the examined phenomenon, which in this thesis is strategic behavior.

The following questions are archetypical for actor analysis;

- Who are the players/actors?
- What are their interests/strategies?

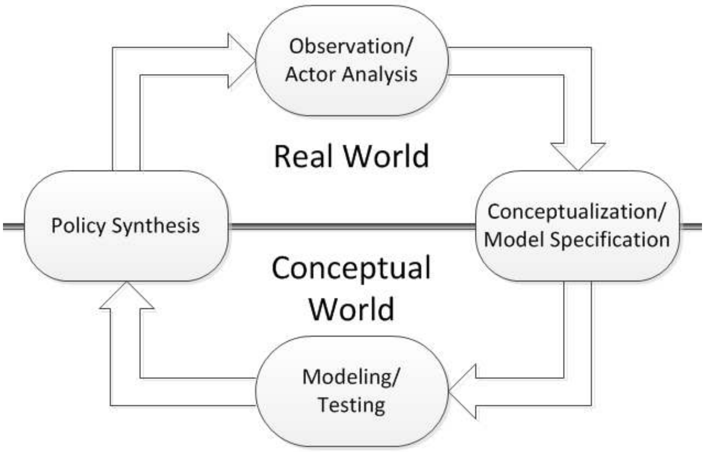

Figure 4.1: Modeling cycle

- How do their interests/strategies intersect each other?
- How can they manipulate the case to serve their self interest?
- How can their potential strategic behavior affect the system?

The liberalization process results in new actors, thus new strategic relations are formed. Our research aims to contribute to the understanding of the effects of this change to various aspects of power systems, such as technical and economical efficiency.

4.4.2 Conceptualization and model specification

The conceptualization and model specification stages of the modeling cycle conceptualize the real-life phenomena into quantifiable, operationalized representations, which are called models. Various details that encompass the modeling behavior, such as utility functions, production functions and cost functions, are structured quantitatively into a model. In a nutshell, conceptualization and model specification is the stage in which the model is built, based on the observations. As described previously, it has utmost importance to explain the reasoning and argumentation behind the basic assumptions at this phase.

As far as the game theoretical formal models are concerned, the conceptualization and specification could be classified into two segments: system models and actor models. Just as in any other quantitative modeling paradigm, game theoretical formal models need to represent the underlying system that serves as a playing field for the actors. Owing to the subject matter of this thesis, the system model concerns the underlying technical and institutional system. For instance, in Chapter 5, the production function and the cost function of the electricity were modeled based on the real data and behavior. These data and behavior represent the underlying system. Similarly in the second case in Chapter 6, the emergence of congestion and locational marginal prices (LMP) were part of the characteristics of the system.

Actor modeling is also important in game theoretical formal models. The determination of the choices (or strategies in game theoretic terms) of the actors is crucial at this stage. What are different choices of the actors? How are the choices of different actors interrelated with each other? How can we quantify the payoffs or utilities of each actor? The determination of the utility functions iss therefore a crucial part of the conceptualization phase. The actor analysis in the observation phase gives some clues about what the utility functions of payoffs for each of the actors might be. The preferences and the valuation of the actors are determined at this stage. The preferences are further reduced to numerical or functional values. Mathematization of the values and preferences enables game theorists to order or at least partially order these preferences and values. Mathematization at this stage gives rise to interesting discussions and theories in game theory literature such as Arrow's impossibility theorem by Arrow (1950).

4.4.3 Modeling and testing

Once the conceptualization and specification are done, modeling and testing are the next steps in the modeling cycle. The modeler harmonizes the conceptualized and specified elements into a coherent unity. Moreover, the testing phase aims to produce meaningful, internally validated behavior in the model.

Two main criteria have to be addressed:

- Do the conceptual models correspond to the researched aspects of the real problem, which are found throughout the examination of empirical data and/or cases? Is there any seemingly important aspect of the problem that does not correspond to any conceptual component or relationship identified in the actor analysis and conceptual analysis phases?
- Are the developed models, which are composed of the proposed set of components and relationships in the modeling framework, capable of reproducing known or anticipated behavior of the respective issue?

The first question corresponds to the verification of the model with respect to the considered actor behavior. In this study, this question is addressed by setting up the models in our modeling approach, whereas the second question corresponds to the validation of the model. This question is answered by simulating the model and inspecting whether the behavior space covers the typically anticipated or known behavior. Depending on the case, if the result is not immediately obvious and data is available, econometric tests help show whether the model is valid.

'Internal validity' is an important qualification that has to exist in any formal model. Given the assumptions, the model behavior should be explainable and accountable. Apart from the specified assumptions, the model should be consistent in its own realm. Different scenarios based on the same model should not conflict with each other.

In the next stage of the modeling cycle, some policy recommendations are given based on the model. These policy recommendations are given while considering the assumptions made in the model. Similarly the policymaker should take these assumptions into account.

For 'external validity', the model assumptions should match the real-life system. The assumptions and the mechanisms that represent the real system should be acceptable for the policymaker. The relevant literature is referred and some interviews with senior policy analysts and economists, who are related to the field of electricity markets, and have greater insight into policymaker perspective than the author of this thesis, are conducted. The relevant literature of the cases is presented within the case chapters, i.e., Chapters 5, 6 and 7. The conducted interviews can be found in Chapter 8, in which policy synthesis and the reflections on the study are presented.

4.4.4 Policy implications

The models built in the preceding chapters are meaningful only if the coherence between the model and the real-life situation is maintained. The linkages between the model and the reality, which are constrained by the assumptions of the model, should always be in mind. Model assumptions should always be discussed in the policy argumentation part. Here critical judgments of the capabilities of the model are made. Although in general modelers have an emotional bond to their own model, this should not lead to a dogmatic belief in the model.

Policy implications coming up from the model can either conflict with or complement the outcomes of other studies on the issue. It always makes sense to discuss the policy argumentations in conjunction with other studies. Applied policies always have to be prepared by taking different perspectives into account. Thus, policy argumentation based on formal models does not suffice as a strong recommendation without taking into account the outcomes of other studies in the literature.

4.5 Policy synthesis

After all the cases are completed, the generated policy insights gathered from each case are synthesized into a general policy argumentation. This part is presented as a separate chapter in this thesis, i.e., Chapter 8. In this chapter gray literature about the usefulness of formal models is presented. Furthermore, some interviews that are conducted to support the outcomes of the research is provided. These interviews aim to validate the study externally.

4.6 Summary

In this chapter the design of the research was elaborated, how the chosen methodology is applied in this thesis to the problem is specified. First of all, game theoretical formal modeling is motivated as the methodology of this thesis. Next, the choice of the cases and thought experiments are motivated and detailed. Then, the modeling cycle and argumentation were provided. Finally, policy synthesis chapter of this thesis was motivated.

While explaining the modeling cycle, the swing between the real world and the conceptual world was described. The modeling methodology was framed as a transformation tool to translate the real-world phenomenon to the human mind by the means formal models.

The next three chapters dwell on three different cases in liberalized electricity sectors. Each of these cases has their own conclusions and policy recommendations in their own right. The subsequent chapter to these three case chapters is the policy synthesis and reflections chapter, which aims to synthesize the outcomes of all three cases and reflect on the course of the study.

Chapter 5

Load-Shifting Price Incentives in Retail Markets

5.1 Introduction

The first four chapters of this thesis constitute the first part of the research and introduce the research domain, research questions, research methodology and the entailing research design. The second part of the thesis, which is composed of this and the following two chapters, presents the actual modeling work. Each chapter in this part presents a cases that refers to a particular strategic behavior in the context of liberalized electricity sectors. Each case is analyzed with the help of an original game theoretical model. This chapter provides the first of these cases, which deals with load-shifting price incentives.

In Chapter 2, newly formed markets in the electricity sectors in the post liberalization era are highlighted, as depicted earlier in Figure 2.4. One of these emerging markets, i.e., the retail market, emerged at the intersection of the activities of two key actors, namely consumers and retailers. The load-shifting price incentive mechanism, which is a mechanism to increase the efficiency of the overall electricity distribution, is analyzed in this chapter.

First, in this chapter, the electricity retail markets and the load-shifting incentive mechanism are explained. A research question regarding the effect of liberalization on the effectiveness of this incentive mechanism is formulated. After a review of similar studies in the literature, an original game theoretical formal model of the problem is produced and displayed. Finally an analysis of the results with some policy recommendations are presented.

5.2 The electricity retail market and load-shifting price incentives

Prior to the liberalization process, electricity retail markets were generally operated by national monopolies in general. The supply chain from the generation plants to the end consumers used to be owned and operated by a single entity, which was the respective national organization in most countries. With the advent of liberalism in electricity sectors all around the world, various new actors emerged between generation and the consumers. At the last stage of the supply chain, electricity retailers began to serve, and the electricity retail market emerged.

During the liberalization process, while generation markets have been designed anew in the form of day ahead markets and residual spot markets. These involve generation companies, retailers and transmission system operators (TSOs). The primary change in retail markets, which involves end consumers (i.e., industrial, commercial and residential consumers) and electricity retailers, has primarily concerned the freedom of the end consumers to choose among multiple retailers. In some countries, the retail business units of unbundled state monopolies have been further divided into smaller companies. In others, the retail market has been opened to national and international energy companies to promote competition. Despite these changes, the end consumers still sign contracts with their electricity retailers as before. As opposed to the generation side, on the retail side, one can talk about a market transformation from a single seller monopoly market to a multiple seller free market rather than a creation of a new market mechanism for energy allocation.

Hence, it is possible to mention a smoother transition in the electricity retail markets as opposed to the electricity generation markets as far as the institutional setting is concerned. The freedom of choice of retailer for the consumers had the advantage of the free market mechanism, which is a surplus for the consumers and, presumably, the general welfare. The competition between the retailers is deemed to increase service quality and decrease prices for the consumers. However, does the competition between multiple retailers as opposed to the monopolistic retailer of the pre-liberalization period cause any side effect that may potentially curb the gains of the free market? Can the retailers alter their actions for their self-benefit in a way that might hinder the general welfare?

It is possible to find an answer to these questions when one considers the greatest challenge of the electricity distribution in the electricity sector, namely peaking demands in electricity usage profile. Because of the unique characteristics of electricity, supply and demand have to be balanced at all times in electricity retail markets, unlike in conventional markets. This is because electricity cannot be economically stored. Because of the lack of storage capacity, electricity companies have always had the problem of forecasting and meeting the fluctuations in electricity demand. The necessity of meeting the demand at peak times results in serious efficiency losses. Load-shifting is thus of interest. In Figure 5.1 the daily electricity consumption profile of the Netherlands is shown for illustration purposes.

The retailers have huge incentives but little means to change and even out the consumer load. However, demand side management (DSM), which deals with peak management, has the ambition of altering consumer behavior either intrusively (e.g., by centrally controlling the energy-hungry devices that belong to consumers (Torriti et al., 2010)) or passively (e.g., by providing price incentives to shift consumer load (Albadi and El-Saadany, 2008)). Load-shifting is aimed to be boosted with the help of various demand response schemes. In this case, the load-shifting price incentives, which are given by the retailers to the consumers to shift their loads to non-peak hours, are analyzed.

load-shifting is the practice of shifting peak energy demand to off-peak time periods. There is no universal definition of off-peak and peak time periods of a particular day. As seen in Figure 5.1, electricity usage is concentrated between 8:30 am and 8:30 pm, which is defined as peak period in this work. Consequently, the terms day/night-time and peak/off-peak period are used interchangeably throughout this research. Electricity shows distinct

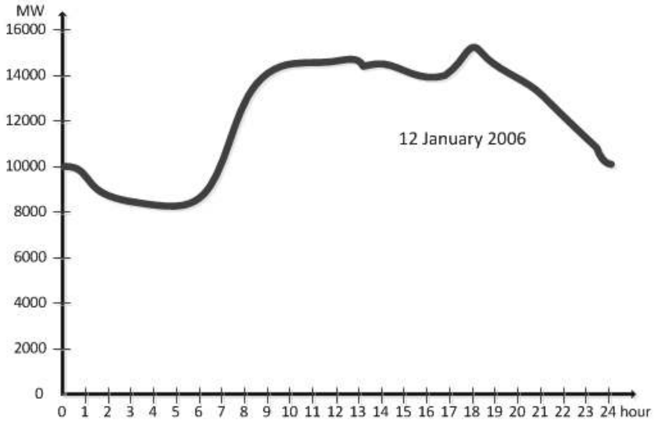

Figure 5.1: Daily load profile of the Netherlands on a particular day in 2006
Source: *Tennet (2006)*

characteristics compared to other commodities in terms of storability.

Although there are available grid energy storage technologies such as plug-in hybrid electric vehicles (PHEV), large-scale batteries, pumped water, hydrogen storage, etc., the storage of electricity is not always economical at large volumes and not widely practiced at the moment (Hunt, 2002). Energy storage is economical when the marginal cost of storing, keeping and dispatching stored energy is less than the cost of producing peak energy. All of the storage technologies impose an efficiency factor due to various physical limitations and losses, including evaporation in water pumping, and conversion losses in battery storage, etc. Hence, storage is widely seen as non-economical in comparison to finding new markets for energy or demand response. This imposes a hard constraint of matching demand and generation at all times. Ultimately, high demand means high generation during peak periods. Instead of cheap plants such as coal fired and nuclear plants, expensive gas turbine plants are fired at peak periods. The fact that some generation plants are rarely used makes their their marginal cost very high. Spees and Lave (2007b) report that in the Pennsylvania-New Jersey-Maryland (PJM) market 15% of electric generation capacity ran less than 96 hours in 2006, which is less than 1.1% of the time.

In complementarity to restructuring in the retail electricity markets, advancements in information and communication technologies (ICT) and increasing pace of adoption of such technologies revolutionized the way we think about the electricity supply and demand match. Newly emerging smart meter technologies, which make use of ICT, show some interesting prospects for enabling retailers to reflect some of their risks and price signals to the consumers. Smart metering, coupled with other information and communication technologies, enables new pricing schemes such as real time pricing (RTP), critical peak pricing (CPP) and time of use (TOU) tariffs. Emergence of these two worlds, namely ICT and the idea of liberalization in public sectors, along with the unsolved load-shifting problem brings about a separate question for electricity sectors. Can we use advanced technologies such as smart electronics, e.g., smart phones, smart meters, smart home appliances, in an attempt to manage demand profile? Can consumer behavior change upon the rich signals coming from the market due to advanced metering services? Should consumers meet real time pricing, that is frequently varying prices reflecting variable wholesale prices or a price set in a hybrid way encapsulating both the advantages of variable pricing and fixed pricing as in the case of the status quo?

In the old paradigm, demand was considered totally inelastic and not price-responsive. Price signals used to not be reflected to the small end users, due to yearly fixed contracts. The recent changes in technology and policy, however, have enabled demand response (DR). Demand response is the label of all the activities that utilities, regulators and the other related stakeholders conducted to shape electricity demand profile. These services are mostly viable for energy hungry industries such as iron and steel industries or petroleum processing and refining because of their initial costs. However, the spread of smart meters is likely to cause different contracts that will make demand response feasible for small consumers too. The advancement in ICT and smart meter technology will likely enable electronic personalized energy managers in residential premises that will do the job in a fairly hassle-free fashion for laymen residential consumers. Having electronic energy managers together with RTP is likely to be the future trajectory that will raise the effectiveness of dynamic pricing to a higher level.

DR efforts date back to mid-1970s, when in California and Wisconsin utilities were ordered by the regulator to work with consumers to increase energy efficiency. In 1978, the Conservation Policy Act mandated utilities to pick up integrated resources planning, the demand side management scheme that envisions peak demand treatment as an alternative to capacity growth (Eto, 1996).[1]

Apart from demand side management programs as mentioned above, building efficiency standards and energy services by energy service companies (ESCO) are also worth mentioning in efforts to change consumer behavior. Efficiency standards mandate that appliance vendors label the electricity efficiency performance of their appliances. This has been another important demand response activity that the respective stakeholders have been conducting, whereas ESCOs aim to provide risk management, energy saving and energy conservation projects to large consumers, i.e., industrial consumers.[2]

Among all these efforts to change customer behavior, dynamic pricing is the prime lever employed by the utilities. Utilities have experimented with time differentiated pricing models for some time now. Hardware availability for real-time electricity monitoring was considered a challenge in early implementations (Tabors et al., 1989). However, a number of smart metering solutions are available in the market today, enabling the implementation of dynamic tariff schemes (Deconinck and Decroix, 2009). Both consumer and utility experience with dynamic pricing were considered to be positive early on. However, the idea of using pricing as a means to change behavior brings about the issue of price elasticity in the electricity retail market. Unfortunate for the electricity industry that consumers are not as sensitive as they are to, e.g., the prices of apples, and consumer electronics or gasoline. However, research shows that well informed consumers are willing to alter their consumption patterns for monetary benefit as in (Faruqui and George, 2005; King and Chatterjee, 2003; QDR, 2006). Among those, Faruqui and George (2005) further quantify customer behavior with changing prices of electricity and provide the base data of consumer behavior

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[1] For a more general discussion on demand response one may refer to (Spees and Lave, 2007a).

[2] The author does not detail these instruments of demand response as they are loosely related to our main concern. More on efficiency standards and ESCOs can be found in (Vine, 2005) and (Meyers et al., 2003) respectively.

in the model in this case, which will be explained in the following sections.

All in all, flat tariffs prove to be inappropriate for modeling of the efficiency of the system for all stakeholders in electricity supply chain. All stakeholders, from generators to consumers, would likely benefit financially from load-shifting.

In the next section model conceptualization is presented, where it is shown how the real market is framed in this work and how load-shifting, competition and the actors in the market are conceptualized. The players considered in this case are modeled in the subsequent section. Then, in Section 5.5 a base case scenario is showcased, where the status quo situation with only the monopoly is presented. Later, in Section 5.6, a change from monopoly to duopoly is investigated and the effect of the duopoly case is presented and discussed. Then the result is generalized in oligopoly case in Section 5.7. A discussion on potential policy implications of the model and the conclusion section conclude the case.

As far as the game theoretical models in pricing domain are concerned, Borenstein and Holland (2003) are some of the first authors to investigate liberalized electricity markets from retail and pricing perspectives. A long-term analysis of real time pricing (RTP), which encapsulates aspects such as capacity investment, optimum wholesale and retail pricing are presented. Mainly, the impact of a partial RTP customer involvement in the market is analyzed. A game between RTP customers and flat rate customers is formulated.

A simple analytical framework was developed in (Pettersen et al., 2005) to capture interaction between network operators, producers and consumers for load-shifting. The approach for the cost functions used in Pettersen et al. (2005) is adopted in this paper to analyze the behavior of the different market participants under TOU tariff pricing under monopoly, duopoly and oligopoly situations.

Furthermore, various papers utilize game theoretical analysis to analyze electricity generation markets, (Amobi, 2007; Haynes et al., 1984; Perez, 2007) accounting important aspects such as capacity expansion and transition cost concerns. Celebi and Fuller (2007) consider volatile wholesale market prices in electricity systems and formulate a model to calculate time-of-use retail prices for a hypothetical restructured retail market. The model utilizes complementarity programming models of equilibrium to estimate *ex-ante* TOU prices for retail electricity markets.

5.3 Model conceptualization

In this case the effect of competition on the load-shifting price incentives in the electricity retail markets is analyzed. Pre-liberalization electricity retail markets and post-liberalization electricity retail markets are compared using game theoretical formal modeling for a hypothetical market setting.

A game theoretic model of the interactions between key market participants is considered, and the dynamics of pricing incentives for electricity load-shifting under varying forms of market competition are analyzed. The interaction between producers, retailers and consumers from a game theoretic perspective under TOU pricing is considered. This interaction between these stakeholders is captured analytically via incentives (i.e., price incentives in our example) and a load-shifting model. The dependence between price incentives and the amounts of load-shifted from day-time to night-time is of interest in this study. First, a single retailer monopoly is considered and a decision model under which the optimum incentive is derived is presented. The game is then extended to a duopoly and oligopoly case. The effects of deregulation and competition are discussed from a game theoretic perspective.

Figure 5.2: Conceptual supply chain

A supply chain is defined to conceptualize the market, as seen in Figure 5.2. The arrows show the flow direction of both the good, i.e., electricity, and the price incentives, as will be explained later.

In an exemplifying game theoretic model, the comprehensibility of the model is crucial. The model should be simple and capture only the related attributes of the real system (Rasmusen, 1994). With this mentality, the transmission system operator (or independent system operator) is omitted in this model. The transmission system operator (TSO) is the actor that is least affected by the liberalization period in terms of competition. The role of the TSO is to control, operate and coordinate the physical and financial transactions between generators and consumers. TSOs have a natural monopoly position in the market chain, as the infrastructure for electricity has single ownership due to its capital-intensive nature. Furthermore, their involvement in the final pricing of the electricity is limited. They usually invoice the retail companies, who in turn, invoice the final consumer.

One approach to facilitating load-shifting is to employ different pricing schemes for day and night-times. Different strategies may be considered for effective pricing. An enabler for effective pricing that allows load-shifting is the deployment of smart meters or any other smart appliance to be utilized at home, such as PCs or cell phones, which can monitor time-of-use (TOU) prices.

In most of the electricity markets, time varying price schemes are not readily applied at the moment, except for the widely utilized TOU tariffs. TOU tariff partitions a day into different price zones, and each zone is priced differently in an effort to create an incentive for the consumer to accommodate its load in the desired time period, i.e., in the off-peak period instead of the peak period. The aim is to create a win-win situation, where both the consumers and the retailer get financial benefit.

To employ TOU tariffs, peak periods of electricity consumption should be determined. There is no universal definition of peak times. In our example the day is partitioned into two equal periods, i.e., taking 8:30 a.m. and 8:30 p.m. as cut-off hours and marking them as peak and off-peak periods, as seen in Figure 5.3. The objective of the retailer is to convince the consumer to shift its load from peak periods to off-peak periods.

5.4 Player descriptions

In this section, the actors of the model – producers, retailers and consumers – are described in a retail electricity market model. In this electricity market, the producers produce electricity in a variety of possible ways and sell it as a commodity to retailers. The retailers

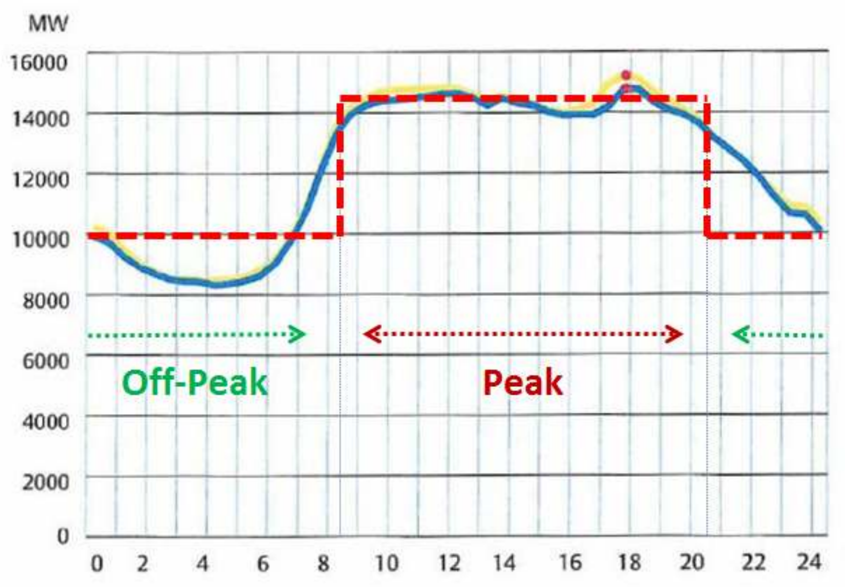


Figure 5.3: Peak and off-peak periods of the daily load profile of the Netherlands

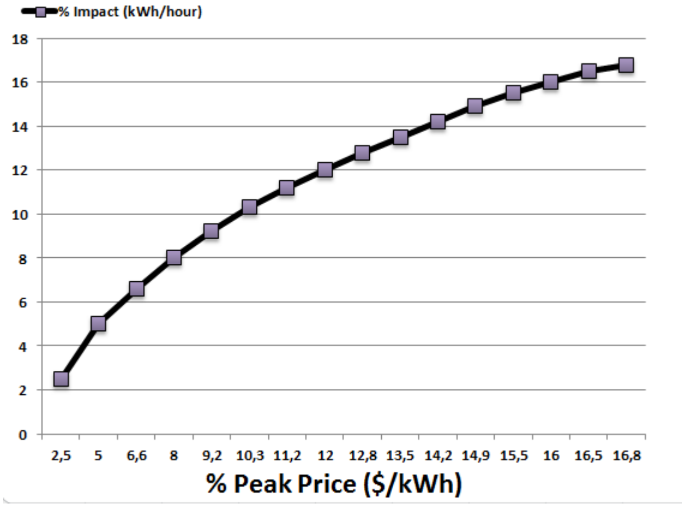
purchase electricity in the wholesale market, re-price it and sell it to end consumers. It is assumed that different retailers who discriminate themselves based on tariff contracts, and homogenous consumers who react to load-shifting price incentives based on comfort and feasibility.

5.4.1 Consumers

In the hypothetical market a certain number, i.e., Q_T number, of homogeneous consumers is assumed. In this market, consumers behave identically in reaction to retail incentives for shifting their load from peak period to off-peak periods. Each of the consumer consumes a fixed amount of energy, which is partitioned into peak and off-peak periods according to the weighting, similar to a typical day in the Netherlands, as in Figure 5.1. Although the rationality and homogeneity assumptions in economic models are highly contested in the literature, in our model these assumptions are made to keep the model simple. On the other hand, these assumptions should be taken into account when deriving conclusions from this study.

The consumers follow the incentives to shift their load. So they are modeled not as decision makers but as decision followers. The decision in this context is the amount of incentives offered by the retailers, which are the players of the game formulate here.

However, there is a cost associated with shifting load for the consumers in terms of comfort, reluctance and feasibility. To estimate this cost we draw from the study of Faruqui and George (2005). In this study, a state-wide pricing pilot experiment in California demonstrates that residential and small to medium commercial and industrial consumers shift their peak loads in response to time varying prices. Furthermore, responsiveness of consumers is quantified in terms of percentage of their load in response to peak price increase. A response curve from this source can be seen in Figure 5.4.



Source: (Faruqui and George, 2005)

Figure 5.4: Price sensitivity of the peak load in California, average summer, 2003/2004

In this figure, the price sensitiveness of consumers in shifting their load is drawn. It shows how the increase of electricity price convinces consumers to shift their load away from peak periods. One can observe in this figure that although the amount of shifted load increases monotonically as the peak price increases, the pace of increase decreases. So we end up with a strictly concave function. Note that although the study of Faruqui and George (2005) is about the Californian market, it is assumed this behavior holds true in general. This assumption is reinforced by the rationale presented in the next paragraph.

The rationale behind this behavior is that shifting first loads for peak time is relatively easy in terms of comfort, compared to the later loads to be shifted. Considering the typical daily routine of a residential consumer, shifting the operation of their washing machine to night-time, which is one of the first things one might consider shifting, is easier than postponing watching a movie to night-time.

Following this reasoning, the cost of shifting load from day-time to night-time is modeled as a strictly increasing convex function, $g(.)$. This is the same modeling choice as in (Pettersen et al., 2005).

In our case the cost of shifting load can be modeled as:

$$g(u) = \begin{cases} -\beta \log \frac{\alpha - u}{\alpha} & \text{if } \alpha > u > 0 \\ \infty & \text{if } u \geq \alpha \\ 0 & \text{otherwise.} \end{cases} \tag{5.1}$$

Here u is the day to night load-shift of one consumer and $g(u)$ is the associated cost to one

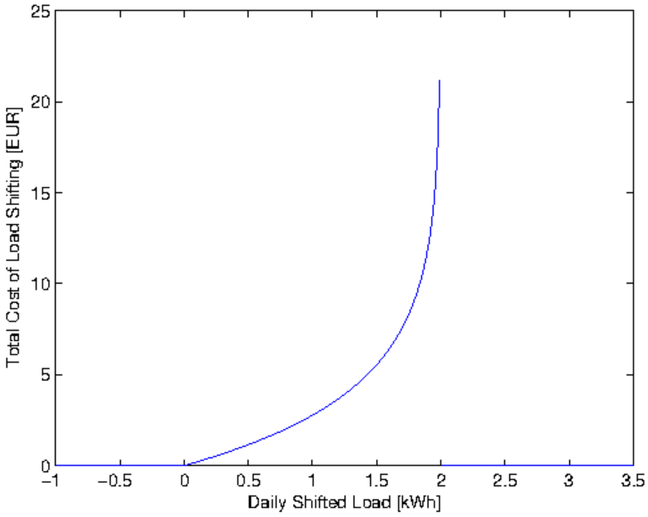


Figure 5.5: Consumer cost for load-shifting

consumer. Model coefficients α and β are positive constants.

The asymptote at α has a character that matches with the real behavior of consumers. In practice, the total shifted load can never be beyond a certain amount of load. This is true because of the fact that some activities, such as watching the World Cup final live, or using an electric oven when you have guests over for dinner can never be shifted to night-time for a particular consumer. The steep behavior in the $g(.)$ function gives the corresponding flavor of reality in our model.

As suggested in the previous subsection, this asymptote also explains the reasoning behind the assumption, which says that the night-time usage never exceeds day-time usage as far as the aggregated behavior is concerned.

Numerical Example:
According to the World Factbook, the Netherlands has a per capita electricity consumption of about 18.5 kWh/person-day (CIA, 2010). The total daily consumption of the consumer is assumed to be at 19 kWh/person-day in our example. Furthermore, the day and night consumptions are assumed to be 16 kWh and 3 kWh, respectively.

It is also assumed that the asymptote, parametrized as α in equation (5.1), i.e., the limit of the amount of load-shift from day-time to night-time, is 2 kWh of load. This load corresponds to the operating consumption of two hours of ironing, one hour of dish washing or half an hour of clothes drying (txspc.com, 2012).

A day-time to night-time shift of this total load matters in terms of the marginal costs of generation, distribution and so on. This load-shift is the main focus of this study.

Having these assumptions, a function $g(.)$ as in equation (5.1) with $\alpha = 2$ and $\beta = 4$ is drawn in Figure 5.5.

5.4.2 Producer

The production is assumed to be already liberalized in this model, which matches with the real-life case in most markets. The wholesale market price is determined either by merit order or with electricity pools as in fully liberalized markets. To explain the rationale clearly, generator dispatching is taken in order of merit as shown in Figure 5.6.

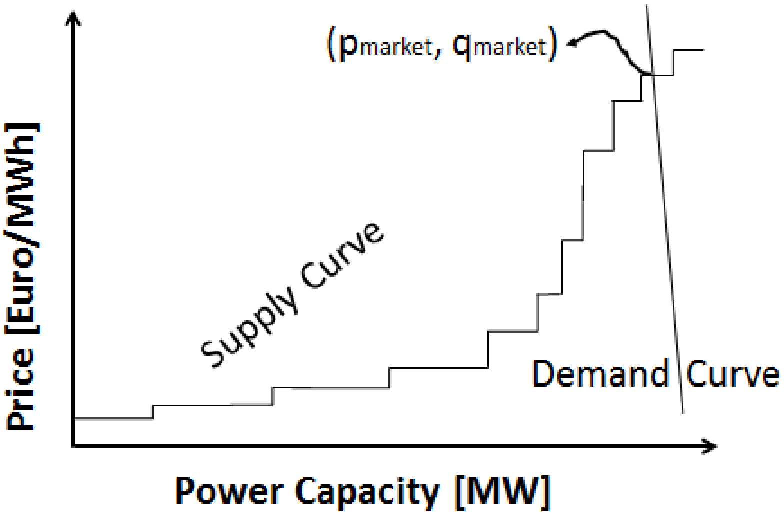


Figure 5.6: Market settlement with generator dispatch in merit order

The generators offer their electricity capacity to the market with associated price bids. Typically a generator offers the marginal cost of running its generation unit to the market. This marginal running cost contains the variable costs of the generation unit and excludes the the sunk investment costs. In reality it is likely that the generation company adds a markup to the marginal running cost. By marginal cost it is meant that the price that the generation company offers in this case.

Different generation technologies impose different marginal costs, which can vary between a couple of euros per megawatt-hour to hundreds of euros per megawatt-hour. As far as the marginal costs are concerned, typically base loads such as nuclear power and coal-fired plants are low-cost generators and natural gas-based plants are expensive. The merit order of various powerplants results in a supply curve as seen in Figure 5.6 (De Vries, 2007; Sensfuß et al., 2008). On the other hand, the electricity demand curve is known to be quite inelastic, as drawn in the figure. The market is cleared at all times. This is indeed the case in electricity markets because of the fact that storage of energy is not an interim process in electricity supply chain (Hunt, 2002).

In order to meet the demand, producers have to utilize expensive generation utilities. Thus load-shifting decreases wholesale price of the electricity in peak period and only marginally increases in off-peak period. In Figure 5.7 the marginal cost and benefit of load-shifting is depicted for an arbitrary amount of shifted load. The blue arrow represents the amount of shifted load. Assuming totally inelastic demand curves DC_{Ni}, which is the initial demand curve of night-time (i.e., off-peak period), the demand curve shifts to DC_{Nf}, i.e., the final night-time demand curve. This move of the night-time demand curve causes a marginal increase in the price of electricity in off-peak time. However, on the other hand, the shift of day-time (i.e., peak period) demand curve shifts from DC_{Di} to DC_{Cf}, resulting in a high price benefit.

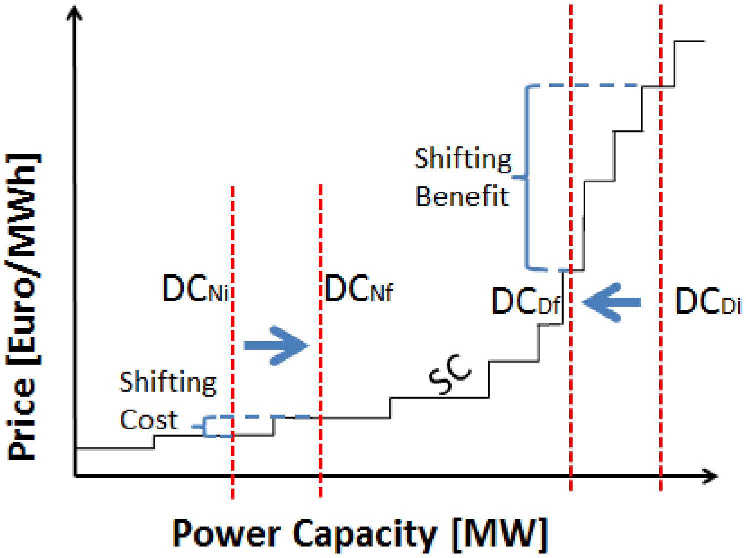


Figure 5.7: Load-shifting cost and benefit

Resultantly, the shift in the electricity load makes the total cost of electricity cheaper for the retailers. The total shift returns to retailers as a discount with a relation as depicted in Figure 5.8. Because of this discount, retailers have a financial incentive to pay consumers to shift their load to low-demand times, e.g., from day-time to night-time. The incentive to the retailer, which stems from the supply-demand relation described above, will be modeled in the retailer description, using the insight described above.

In our model, the producer is concerned with the total shifted load in MWh. As more consumers shift their load from day-time to night-time, the retailer can have cheaper electricity based on the total load on the network. Generally in various markets retailers have this sort of incentives (i.e., a decrease in wholesale prices) for convincing consumers to shift their load to night-time, although peak times may vary (Skytte and Ropenus, 2005).

5.4.3 Retailer

As explained so far, a large amount of load during the day-time is undesirable for the retailer. During the day, electricity consumption approaches critical levels, which makes the cost of unit electricity excessively high for the retailers. Thus the retailer is interested in maximizing its total revenue over day and night-times, which is tied to the electricity consumption pattern of consumers and to the wholesale price of electricity.

In this model the retailer chooses the amount of price incentive that maximizes its revenue. This decision is based on a trade-off between the financial benefit due to the discount on the wholesale (producer) side and the costs of incentive payment to the consumers.

Let the night and day prices be denoted by p_N and p_D, respectively. The retailer is interested in setting an optimal incentive payment, which is the strategy of the player in game theoretical terms, r, for night-time consumption, where

$$r = p_D - p_N. \tag{5.2}$$

The discount of wholesale price that retailers can benefit from a total shifted load of L is modeled as

$$f(L) = \begin{cases} \gamma(1 - e^{-\frac{L}{\theta}}) & \text{if } L > 0 \\ 0 & \text{otherwise} \end{cases} \tag{5.3}$$

where model parameters γ and θ are positive constants. The function $f(.)$ is the incentive per consumer that the retailer benefits. All the Q_T numbers of consumers shift u amount of load. Hence, the total shifted load, which can be expressed as $Q_T u$, is in the interest of the producer and this amount of total load-shift determines the price, as explained in 'Producer' Subsection.

Numerical Example: For the choice $\gamma = 30$ and $\theta = 600$, the incentive function in terms of the total shifted load is depicted in Figure 5.8.

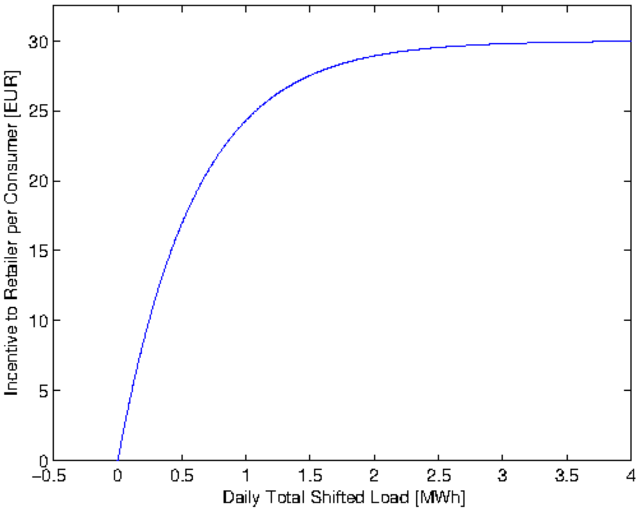


Figure 5.8: Incentive for total shifted load for retailer

Note that in our model, it is assumed that each consumer consumes the same, fixed amount of electricity, although they may prefer to shift some load from day-time to night-time (e.g., running a washing machine at night-time instead of during the day-time) given the right amount of incentive to compensate the burden of shifting the load . Let x_D and x_N be the amounts of consumption of one typical consumer during day-time and night-time, respectively. The function $f(L)$ corresponds to the decrease in procurement price of a unit of electricity as seen by the retailer. It is assumed that the procurement price for retailer is fixed. That is to say, for both day and night-times, the price is assumed to be the same. If one calls this price P_p, the price of total generated electricity for the retailer is $P_p(x_P + x_N)Q_T$, where $x_P + x_N$ is the total consumption of a consumer, at status quo. In case some load is shifted by the consumers, the total price becomes $P_{p_{new}}(x_P + x_N)Q_T$, where $P_{p_{new}} < P_p$ due to efficient generation. In our model $f(L)$ represents the difference between these two total prices per consumer, that is $(P_p - P_{p_{new}})(x_P + x_N)$. Since all the consumers consume the same amount, here the incentive per 'consumer' is modeled instead of per 'unit load consumed by one consumer', since these practically have the same implications for the model.

This incentive paid to the retailer can be considered as 'the discount of the wholesale electricity price'. This function is quite intuitive in this sense. By shifting the load, the most expensive electricity production is cut off initially. Hence, the discount on electricity price is steeper for the first incremental shifted load amounts. This discount is reflected to the retailer as in the function, though. Its behavior can last up to a point where the load is balanced. Thus it has an horizontal asymptote at γ. The reasoning and the empirical data it depends on was explained in the 'Producer' Subsection.

Of course one can argue that if load is shifted beyond 'balance point', which can be defined as the shifted load which brings the night-day balance to the system, then the day-time becomes the cheaper period. Hence, the discount function has to drop after the balance point. It is assumed this would never be the case in our model. This makes sense, since the cost of shifting too much load to the night would be costly for consumers and even infeasible from a practical perspective.

5.5 Decision model: The monopoly case

The market works in such a way that the producer produces and provides electricity to the retailer, who in turn re-prices and delivers it to the consumers.

First of all, consider the producer. In our market model, the producer is a perfect market providing a commodity. The electricity price that wholesale markets settle for is bounded by the marginal cost of electricity submitted by the generators. The price charged by the producer is assumed to fixed according to the total demand at peak time and off-peak time periods. The off-peak time demand is assumed to be low in comparison to peak time period. And the amount of load-shifted from peak time to off-peak time reflects to the wholesale electricity price as a discount, as explained in Subsection 5.4.2.

Now let us consider the consumers. The consumers' interest is to minimize their cost function, resulting in the following optimization problem:

$$\min_u \{g(u) + p_D(x_D - u) + p_N(x_N + u)\}. \tag{5.4}$$

Here, $x_D + x_N$ is assumed to be constant. The shifted load u can be adjusted by the consumer for its own interest. In all cases the consumer is assumed to be perfectly rational and follows the offered incentive. Although this assumption of a rational consumer seems unreasonable at first sight, one can consider it as an approximation of the collective consumer behavior, coupled with the comfort cost mentioned in equation (5.1).

Using (5.2), one can cast equation (5.4) into the following form for a given r:

$$\min_u \{g(u) - ru + p_D x_D + (p_D - r)x_N\}. \tag{5.5}$$

Then the optimal amount of shifted load, $\bar{u}$, satisfies the following equation:

$$\frac{\partial g(u)}{\partial u}|_{u=\bar{u}} - r = 0. \tag{5.6}$$

If one take $g(.)$ as in equation (5.5), following our example the optimal shift for a given r is found as

$$\bar{u} = \frac{-\beta + r\alpha}{r}. \tag{5.7}$$

Now consider the TOU retailer. The producer offers an incentive for the shifted load by consumers, which is related to load-shifting purposes of the producer as previously explained. For this example, an $f(L)$ is assumed, as in equation (5.2).

Then a TOU retailer, assuming that it is the sole retailer in the market, is interested in maximizing the following profit function:

$$\max_{p_D} \{f(\bar{u}(r)Q_T)Q_T + p_D(x_D - \bar{u}(r))Q_T + p_N(x_N + \bar{u}(r))Q_T\}. \tag{5.8}$$

under the constraint $p_N = p_D - r$, with p_D being constant. Equation (5.8) can be cast into the following form

$$\max_r \{f(\bar{u}(r)Q_T)Q_T - r\bar{u}(r)Q_T + p_D x_D Q_T + (p_D - r)x_N Q_T)\}.$$

or equivalently,

$$\max_r \{f(\bar{u}(r)Q_T) - r(\bar{u}(r) + x_N) + p_D(x_D + x_N)\}. \tag{5.9}$$

Equation (5.9) results in the following optimality condition:

$$[\frac{\partial f(\bar{u}Q_T)}{\partial u} Q_T - r]\frac{\partial \bar{u}}{\partial r} - (\bar{u} + x_N) = 0. \tag{5.10}$$

At this point, if one considers (5.6) and takes derivative with respect to r, one has

$$\frac{\partial^2 g(\bar{u})}{\partial u^2}\frac{\partial \bar{u}}{\partial r} = 1. \tag{5.11}$$

Following equation (5.11), equation (5.10) can be written as

$$\frac{\partial f(\bar{u}Q_T)}{\partial u} Q_T - r = \frac{\partial^2 g(\bar{u})}{\partial u^2}(\bar{u} + x_N). \tag{5.12}$$

Proposition 1 *For equation* (5.12)*, only one solution may exist.*

Proof: $f(.)$ is a concave function, which implies $\frac{\partial^2 f()}{\partial u^2} < 0$; hence $\frac{\partial f(\bar{u}Q_T)}{\partial u}$ is a decreasing function of $\bar{u}$. $-r$ is also a decreasing function of $\bar{u}$ by definition. Thus the left hand side of the equation (5.12) is strictly decreasing.

On the other hand, since $g(.)$ is assumed to be a strictly increasing, convex function, the right hand term $\frac{\partial^2 g(\bar{u})}{\partial u^2}(\bar{u}+x_N)$ is strictly increasing. Thus these two curves can intersect at most at one single point. □

For illustration purposes, $f(.)$ is assumed as in equation (5.3) and $g(.)$ as in equation (5.1).

Twice differentiating $g(u)$ in equation (5.1) for $u > 0$ the following is found:

$$\frac{\partial^2 g(\bar{u})}{\partial u^2} = \frac{\beta}{(\alpha - \bar{u})^2}. \tag{5.13}$$

Using equations (5.13) and (5.12), we come up with the $\bar{u}$, r pair satisfying the following two equations:

$$r = \frac{\beta}{\alpha - \bar{u}} \tag{5.14}$$

$$\frac{\gamma Q_T}{\theta} e^{-\frac{uQ_T}{\theta}} - r = \frac{\beta}{(\alpha - \bar{u})^2}(\bar{u} + x_N). \tag{5.15}$$

Numerical example:
Continuing our numerical example and assuming the consumer nominally consumes $x_N = 3$ kWh at night, we find $r = 3.29$ and $u = 0.78$ for a single retailer and a population of $Q_T = 1000$ consumers using equations (5.14) and (5.15).

If we compare this state to the no-incentive state, for which electricity is priced at p_D all the time, the consumer's profit can be calculated as

$$\begin{aligned} \text{ConProfit} =& -\{g(\bar{u}) + p_D(x_D - \bar{u}) + (p_D - r)(x_N + \bar{u})\} \\ &+ \{p_D(x_D + x_N)\} \qquad (5.16) \\ =& r(x_N + \bar{u}) - g(\bar{u}) \qquad (5.17) \end{aligned}$$

which would be 10.46 EUR. The retailer's profit per consumer would be 9.43 EUR/consumer. These values are the optimal values that both the retailer and consumer would get for the described market. The producer also enjoys a load-shift of $u = 0.78$ kWh in this case.

These results are obtained when there is a retailer monopoly. However, in the current liberalized electricity market, the retailer no longer has monopoly. Thus in the next section a game is modeled where two retailers are interested in pushing for a consumer shift in order to profit from incentives offered by the producer.

5.6 Duopoly game

In the previous section, the tactical maneuvers of consumers and a single retailer are discussed in the modeled electricity market. The consumers are interested in minimizing electricity costs by shifting their loads to night-time. However, while doing this, they have to find a compromise between their comfort and gained surplus. From the perspective of the retailer, the situation is a bit more complicated as it has to consider the amount of discount coming from the producer while taking into account the reaction from the consumer.

In this section, two identical retailers are assumed, namely *retA* and *retB*, each of which has half of the market share, i.e., $Q_A = \frac{Q_T}{2}$ and $Q_B = \frac{Q_T}{2}$, as depicted in Figure 5.9. These retailers share the same electricity pool to procure electricity. Thus the discount coming from the producer is dependent on the both retailers' actions due to equation (5.3).

In duopoly game two players, i.e., the retailers *retA* and *retB*, offers their respective price incentives to their respective consumers. Thus they both try to incentivize their own consumers for load-shifting using their price incentives. The price incentives are the strategies of the retailers. The resulting benefits due to load-shifting are shared by the retail companies through decreasing wholesale electricity prices. These benefits subtracted by the costs for the offered price incentives constitute the payoffs for the players. In this duopoly game, a Nash equilibrium (NE) is to be found for the amounts of price incentives offered by the retailers.

Nash equilibrium is a state when the players in a game cannot do better by unilaterally changing their respective strategies. Since no player changes its position, the state is said to be an equilibrium. The NE in our duopoly game determines the amount of price incentive offered by the retailers. Later these NE incentives are compared with its monopoly counterpart.

5.6.1 Producer and consumers

In this case, the producer behaves according to the shifted load as described in equation (5.3). The producer is interested in the 'total' load-shift and accordingly pays a discount.

The situation for a single consumer also does not change. The consumer follows its

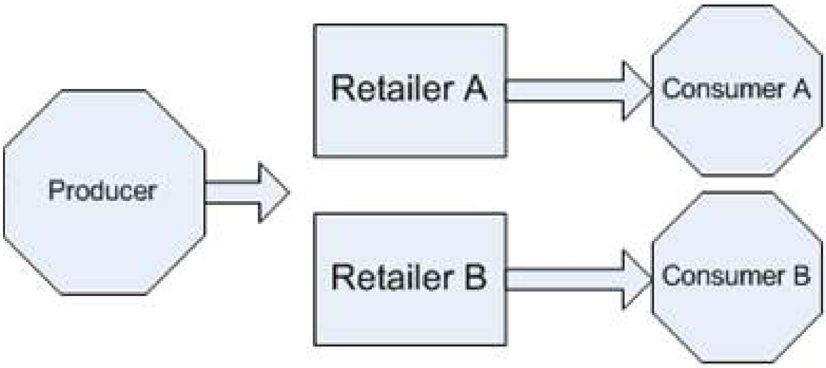


Figure 5.9: Duopoly market chain

associated retailer's incentive based on the cost function (5.1). In this respect one can consider it to be a follower in the Stackelberg game sense (Basar and Olsder, 1999). Note that in a Stackelberg game the leader player moves first and then the follower firms move sequentially, which is exactly the observed behavior in the model.

5.6.2 Retailers

From the perspective of the retailers, the incentive expected from the producer varies according to the opponent's move. Thus the *retA*, without loss of generality, confronts the following optimization problem:

$$\max_{r_I}\{f(L)Q_I - r_I\bar{u}_IQ_I + p_Dx_DQ_I + (p_D - r_I)x_NQ_I\} \tag{5.18}$$

where the total shifted load L is

$$L = \sum_{I\in A,B}(\bar{u}_IQ_I). \tag{5.19}$$

Here in equation (5.18) r_I is the strategy of *retI* for this game, where $I \in \{A,B\}$. Likewise $\bar{u}_I$ is the shifted load for the corresponding retailer.

The strategies r_A and r_B are two strategies chosen from the interval $[0,\alpha)$ according to our example. p_D is fixed as in the one retailer case. The game is a continuous noncooperative game.

In the next subsection a Nash equilibrium (NE) is found for this game.

5.6.3 Nash equilibrium

In this section, it is assumed that the retailers have perfect information about their cost and incentive functions and the consumers' cost and incentive functions, but do not know about their opponent's strategy. *retA* and *retB* denote Retailer A and Retailer B, respectively. The consumers of both retailers behave in the same manner as in the first part since from the consumer's perspective the situation has not changed at all. Then the consumer group for each retailer reacts to a particular u_I by choosing

$$r_I = \frac{\beta}{\alpha - \bar{u}_I}. \tag{5.20}$$

Through a similar reasoning, one can inherit the equations (5.11) and (5.13) directly as:

$$\frac{\partial^2 g(\bar{u}_I)}{\partial u_I^2}\frac{\partial \bar{u}_I}{\partial r_I} = 1, \tag{5.21}$$

$$\frac{\partial^2 g(\bar{u}_I)}{\partial u_I^2} = \frac{\beta}{(\alpha - \bar{u}_I)^2}. \tag{5.22}$$

However, the situation for retailers is different from that in the monopoly case. As the retailers share the same producer, the rival retailer's action affects the payoff. The incentive per consumer, $f(L)$, that the producer would pay can be written analytically, using equation

(5.19), as follows:

$$f(L) = \gamma(1 - e^{-\frac{(\bar{u}_A Q_A + \bar{u}_B Q_B)}{\theta}}). \tag{5.23}$$

retA wishes to choose r_A that solves equation (5.18), which gives the following condition:

$$\frac{\partial f(L)}{\partial r_A} - (\bar{u}_A + x_N) - r_A \frac{\partial \bar{u}_A}{\partial r} = 0, \tag{5.24}$$

where

$$\frac{\partial f(L)}{\partial r_A} = \frac{\gamma Q_A}{\theta}(e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}})\frac{\partial \bar{u}_A}{\partial r}.$$

Then equation (5.24) becomes

$$(\frac{\gamma Q_A}{\theta} e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}} - r_A)\frac{\partial \bar{u}_A}{\partial r} = \bar{u}_A + x_N. \tag{5.25}$$

Using equation (5.25), (5.21) and (5.22) we get

$$\frac{\gamma Q_A}{\theta} e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}} - r_A = \frac{\beta}{(\alpha - \bar{u}_A)^2}(\bar{u}_A + x_N). \tag{5.26}$$

Similarly, for *retB*, we obtain

$$\frac{\gamma Q_B}{\theta} e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}} - r_B = \frac{\beta}{(\alpha - \bar{u}_B)^2}(\bar{u}_B + x_N). \tag{5.27}$$

Then the NE solution for both retailers must satisfy the following four equations

$$r_A = \frac{\beta}{\alpha - \bar{u}_A} \tag{5.28}$$

$$\frac{\gamma Q_A}{\theta} e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}} - r_A = \frac{\beta}{(\alpha - \bar{u}_A)^2}(\bar{u}_A + x_N) \tag{5.29}$$

$$r_B = \frac{\beta}{\alpha - \bar{u}_B} \tag{5.30}$$

$$\frac{\gamma Q_B}{\theta} e^{-\frac{\bar{u}_A Q_A + \bar{u}_B Q_B}{\theta}} - r_B = \frac{\beta}{(\alpha - \bar{u}_B)^2}(\bar{u}_B + x_N). \tag{5.31}$$

The game features of the behavior originate from the quantity interactions of the retailers' utility.

Numerical example:
If we continue with our numerical example with $Q_A = Q_B = \frac{Q_T}{2} = 500$ then $u_i = 0.57$ and $r_i = 2.79$ are found for both consumers as the Nash Equilibrium (NE) of this game by solving equations (5.28)-(5.31). Each consumer's profit becomes 8.62 EUR and the profit per consumer of each retailer becomes 8.38 EUR.

This point is indeed the NE (Nash, 1951) as unilateral deviations from the Equilibrium constitutes loss for the corresponding player. To illustrate this, we can consider the total profit function of *retA* in terms of r_A in case *retB* plays NE, i.e., for $r_B = 2.79$.

The total profit of *retA* in terms of *retA*:

$$\begin{aligned} Prof_A = &\{p_D(x_D - \bar{u}_A) + (p_D - r_A)(x_N + \bar{u}_A)) + f(L)\} \\ &- p_D\{(x_D + x_N)\} \qquad (5.32) \\ = &- r_A(x_N + u_A) + f(L) \qquad (5.33) \end{aligned}$$

which is shown in Figure 5.10.

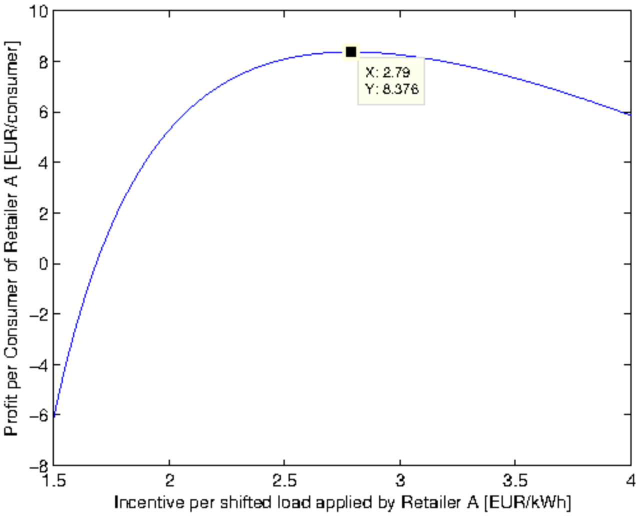


Figure 5.10: retA Total profit function if retB plays Nash Equilibrium

This result shows that when the retailer is broken into two identical retailers, the global welfare worsens, since the resulting incentive drops in this case. The global welfare is directly proportional to the optimal price incentive. The decrease in the retailer incentive results in less load-shift, which is not beneficial for either player.

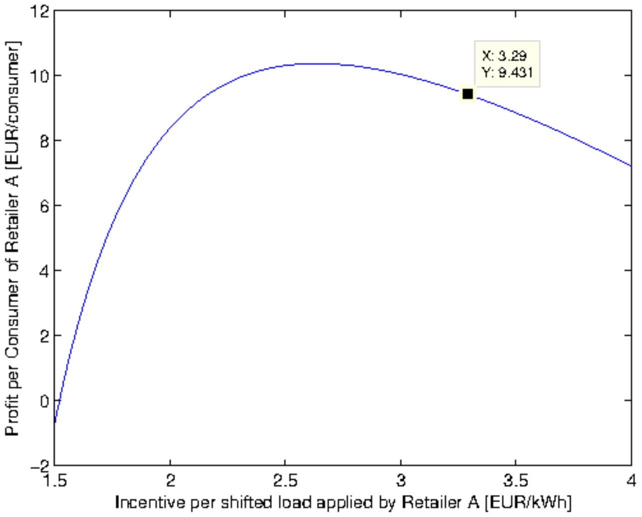


Figure 5.11: RetailerA Total profit function if RetailerB plays NE

5.6.4 Repeated duopoly game

In this section, contrary to the previous one, we assume that the retailers do not know about their opponent's incentive costs or benefits. Then a particular retailer, say *retA*, has to decide how much r_A it would apply.

Suppose both retailers behaved naively and analyzed the situation in a similar way to come up with the results obtained in section 5.5 and played $r_A = r_B = 3.29$, as found in the respective section. Then, just as in the single retailer case, both retailers gain a profit of 9.43 EUR/consumer and consumers get 10.46 EUR. This makes sense, since there is no difference between a two-retailer case and a one-retailer case apart from the fact that two retailer case is formed by splitting the retailer in the one retailer case into two identical retailers. These two retailers share the same producer and the same number of consumers. Thus in case they collude they would play exactly the same $r = 3.29$.

However, this is not an Nash Equilibrium as can be observed in Fig. 5.11, with $r_B = 3.29$ and r_A taken as an independent variable.

Then *retA* decreases its incentive r_A to achieve a better payoff. Note that although this point is not an NE, it is more profitable for all the stakeholders compared to the NE solution. This situation will be illustrated later as a Prisoner's Dilemma.

The repeated game and the implications of the corresponding states on the profits of consumers and retailers is tabulated in Table 5.1. This table clearly shows that in case the retailers do not cooperate they fall into a conflict and gradually are steered to the NE. The evolution of the game, which results in the NE solution, is not beneficial for all of the stakeholders, namely the consumers, the producer and the retailers. Thus the game is a Prisoner's Dilemma, as shown in Table 5.2, in which cooperation leads to a benefit for everyone whereas defection leads to a loss-loss-loss situation.

Table 5.1: Evolution of the Game with steps of $\Delta r_I = 0.10$

Repeated Game								
t	r_A	r_B	PR_A	PR_B	u_A	u_B	PC_A	PC_B
1	3.29	3.29	9.43	9.43	0.78	0.78	10.46	10.46
2	3.19	3.29	9.67	9.17	0.75	0.78	10.08	10.46
3	3.19	3.19	9.40	9.40	0.75	0.75	10.08	10.08
4	3.09	3.19	9.60	9.10	0.71	0.75	9.71	10.08
5	3.09	3.09	9.29	9.29	0.71	0.71	9.71	9.71
6	2.99	3.09	9.45	8.95	0.66	0.71	9.34	9.71
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
11	2.79	2.79	8.38	8.38	0.57	0.57	8.62	8.62

Table 5.2: Prisoner's Dilemma

		r_A	
		3.29	2.79
r_B	3.29	(9.43,9.43)	(7.81,10.31)
	2.79	(10.31,7.81)	(8.38,8.38)

5.7 Oligopoly game

This section focuses on the case when there are more than two retailers competing in the modeled electricity market. The resulting market is an oligopoly market with identical players, which is a natural extension of the duopoly case. Conclusions for a perfect market can be made from this section.

Let S be the set of retailers and N be the number of retailers. Then the NE must satisfy the following $2N$ equations;

$$r_X = \frac{\beta}{\alpha - \bar{u}_X} \tag{5.34}$$

$$\frac{\gamma Q_X}{\theta} e^{-\Sigma \frac{\bar{u}_i Q_i}{\theta}} - r_X = \frac{\beta}{(\alpha - \bar{u}_X)^2}(\bar{u}_X + x_N) \tag{5.35}$$

where $X \in S$.

Numerical example:
Following our Numerical Example with $Q_X = \frac{Q_T}{N} = \frac{1000}{N}$, we come up with the decreasing load-shift against an increasing number of retailers. In Figure 5.13, it is shown that the load-shift for NE solution approaches to zero as the number of retailers increases. Also in Figure 5.12, it can be seen that the optimal incentive decreases with an increased number of retailers. In other words, chopping the incumbent monopoly into equal size of retailers leads to a counter incentive for retailers to propose discounts for load-shifting.

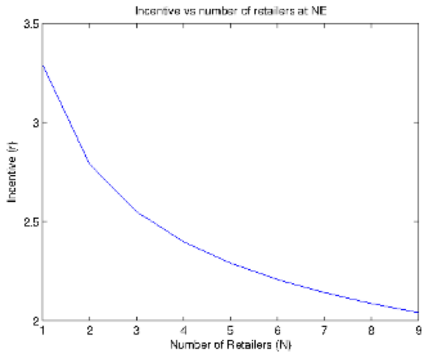


Figure 5.12: Incentive at NE vs number of retailers

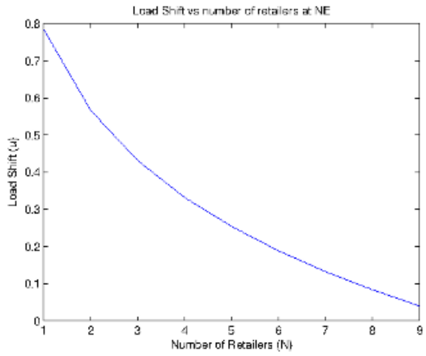


Figure 5.13: Load-shift at NE vs number of retailers

5.8 Conclusions and policy implications

The currently ongoing liberalization of the electricity markets faces many challenges due to the unique and complex characteristics of the electricity system. The whole system is going through changes, which have various consequences to the institutional, social, environmental, political and economic settings of electricity systems.

One important challenge electricity sectors face is an increasing electricity demand. The immediate response to the increasing electricity demand by consumers is to increase the generation capacity. The supply side of the supply-demand equation is under the control of utility companies, who build their generation capacity continuously. Moreover, on the other side of the equation, demand can be modified in order to maintain supply demand balance. Demand side management (DSM) has the ambition to influence consumer demand by paying price incentives to the consumers. Modifying the demand would not necessarily mean decreasing the overall demand. Shaping the demand load profile would also result in efficiency gains for electricity allocation. In this context, load-shifting price incentives are an important lever to increase the overall efficiency of the electricity system.

The efficiency of the electricity markets is high on the agenda of policymakers, since it touches upon various high priority issues such as energy crises, green energy and climate change, in addition to the aforementioned increasing energy demand. Motivating the load-shifting behavior from peak time periods to off-peak time periods would mean an increase in the overall efficiency of the system.

In this study, the effect of competition in electricity retail markets on demand side management, specifically load-shifting price incentives, is examined. A hypothetical electricity market is analyzed by utilizing a game theoretical formal model to deduce some insights about the underlined effect.

An incentive game between the fundamental stakeholders of a hypothetical supply chain in an electricity market was set up. Initially the model consisted of a supply chain model with a monopoly. In this decision model, the optimal incentive for load-shifting for such a monopolistic retailer is formulated and solved as a single variable optimization problem. Later the incumbent retailer transformed into two identical companies with equal customer base *ceteris paribus*. Hence, in the model the effect of the unbundling of an incumbent retailer into two identical retailers on the load-shifting price incentives is observed without considering consumer competition between the retailers. The model describes a two player game in which the retailers compete by altering their respective load-shifting price incentives. The game revealed that the Nash equilibrium solution gives a worse global welfare in the oligopolistic case compared to the monopolistic case with regards to the load-shifting incentive mechanism. All the stakeholders leave worse off when the number of retailers increases.

The conclusions of the modeling study show that when retailer companies share the same electricity source, which is a common wholesale electricity market in our case, the retail companies have less incentive to offer load-shifting price incentives in comparison to the monopoly case. The price incentive offers by the retailers induces the consumers to shift their load. The offered price incentives are costs for the particular retailers who pay for the incentive offers. However, the load-shifting behavior of the consumers benefits all the retailers together because of the decreasing prices of wholesale electricity. Hence, essentially by offering price incentive, a particular retailer does a favor not only to itself but for all the retailers in the market. However, as the retailers are broken into smaller retailers, larger chunk of the benefit from the load-shifting goes to the rest of the market than the paying retailer itself. It is shown that when a monopoly retailer is divided into two or more retailers, the independent retailers begin to decrease their respective price incentive offers while still benefiting from the incentive offers by the other retailers. Since the retailers begin to ride on the price incentives of the other retailers and begin to offer fewer price incentives themselves a free-riding effect is observed.

Based on these observations, some comments may be made on policies related to load-shifting price incentives. The liberalization process of the electricity retail market might be complemented with an independent regulatory body that would assess the incentive regulation. Either a regulatory body can mandate a level of load-shifting price incentive or the retail companies may organize themselves to agree on a level of price incentive themselves. On the other hand, it is worth noting that the latter option might lead to price fixing, which would result in a more detrimental market failure. However, the first option can still be implemented as a price regulation. As an example, the incentive amount, in the form of the difference between day-time price and night-time price, could be mandated to be above a certain threshold. Or the regulator could offer a mechanism that turns load-shifting incentives into a cooperative game between the retailer companies. Measures of this sort would be beneficial for all stakeholders including the electricity retail companies themselves according to our analysis.

It is important to note that the model in this case is framed by various assumptions, one being that the consumers are assumed to be homogeneous and rational. Although there are various accounts in the literature that oppose them, these assumptions are made for the sake of simplicity and clarity of the model. Concerning the effects of these assumptions on the outcome, it is possible to say that these assumptions are reasonable in our context. The relevant behavior of the consumers in the model is that collectively they respond more to a higher price incentive than to a lower price incentive. Since this resulting behavior is reasonable with respect to the real-life behavior as demonstrated by Faruqui and George (2005) and in Figure 5.4, which quantifies the responsiveness of the consumers in Californian market, the effects of these assumptions on the outcome is quite minimal.

The more severe assumptions that are made throughout the model are the assumption of fixed retail price during day and no competition between the retailers over the consumers. In contrast to day-time price, night-time price is allowed to be changed with the offered price incentives. One can argue that the competing retailers in duopoly and oligopoly games can cut their day-time prices as well as night-time prices to compete for capturing consumers from each other. Although a competition over the consumers would change the game, the author counter-argues that the competition dynamics would unnecessarily complicate the model and overshadow the point of the study. The point of the model is that the incentive offers, among others, discount on night-time usage and becomes less beneficial for the individual retailers with the increasing number of retailers due to the common wholesale market and shared benefits. So the individual retailers have increasingly less incentive to offer low night-time prices with an increasing number of retailers. Although the author claims that the competition over consumers is a different game and does not affect the point of this study, exploring this addition could be an interesting follow-up to this study.

Chapter 6

Financial Transmission Rights

6.1 Introduction

In the previous chapter, the effect of competition on the electricity retail market, specifically on demand side management, is investigated. The adverse effect of strategic behavior of market participants is shown in the context of load-shifting incentive mechanisms. In Chapter 2, a particular strategic behavior in wholesale electricity markets is examined. This chapter places the electrical transmission grid and a particular congestion management method in relation to the wholesale electricity markets under scrutiny.

In this chapter, first, a particular strategic management issue, i.e., congestion in the electrical transmission grid, is described. While highlighting the principal policy options in conjunction with the described strategic management issues, a brief survey of congestion management methods is proposed under two categories: physical transmission rights and financial transmission rights. Finally, a coupled electricity market - financial transmission rights model is formulated in Section 6.5.2. The model emulates a scenario which highlights a potential strategic behavior by the generation companies. In this example a particular strategic behavior, which is based on hidden knowledge of generation capacity enlargement, is exemplified and strategy-proneness of the FTR markets is demonstrated.

6.2 Transmission Congestion Management

Every networked infrastructure needs to be treated in light of its particular technical functionalities as well as associated social and political acceptances. The electricity system is not different in this regard, given its broad application field that affect three-quarters of all people on Earth (Gronewold, 2009) and its very complex technical specifications. These specifications include but are not limited to storage problems, the requirement of market clearance and loop flows. Safeguarding these critical technical specifications, which emerge from the very nature of these industries, is an obligation. In some situations strategic behavior exercised by the competitive companies of the deregulated markets may hinder the delivery of the critical service (Borenstein and Bushnell, 1998).

Congestion in transmission lines is a particular phenomenon to be considered in this regard (Knops et al., 2011). Thermal limits, voltage stability and voltage drop regulations impose transmission capacity limitations on transmission lines. Thus distribution of electricity flows among the transmission lines should be regulated in order not to exceed these transmission capacity limits. Owing to this fact, many congestion management methods have been devised in the literature (Kumar et al., 2005) and many of these are actually utilized in various electricity markets (De Vries, 2004).

Electric power transmission systems are utilized to transfer bulk electricity from generators to loads. The transmission occurs on the transmission networks or power grids, which is comprised of high voltage transmission lines. These transmission lines cannot carry beyond a certain limit, which is dependent on the heat related properties of the cable. Electricity transmission congestion refers to situations in which this limit is reached and no marginal megawatts can be pushed into the transmission network. The effects of congestion over a line can jeopardize the security of the entire system. A higher quantity of permitted flow through the line might overheat it, causing elongation of the material, which in some cases can be permanent. This situation increases the probability of failure or even blackout and carries severe social and economic consequences (Fang and David, 1999).

The liberalization process, at the first stage, aims to unbundle the vertically integrated electricity infrastructure into separate entities. Thus the aim is to delegate generation, transmission and distribution responsibilities to different entities, most of which would naturally be private firms. Among these operations, the transmission system, which carries the electricity from the generators towards the distributors, has a very critical role in safeguarding the security and reliability of the system. One of the challenges is managing the flow over capacity-limited transmission lines.

The current trend in electricity industry liberalization has created a large number of market players. This, in turn, raises the complexity of the coordination among the unbundled parts of the system. Since monopolies have the ability to control both the generation and the transmission system, they could allocate the flows such that the capacity limits are not exceeded (Ruff, 1999). The monopoly dispatcher could simply instruct some plants to produce a bit more and some to produce a bit less until the system is balanced within transmission constraints, and none of them would have much reason to resist because they all share the costs and profit in an internal pool. However, in a free market setting the situation is very different.

According to general equilibrium theory, a market is called perfect if information is transparent, no barriers of entry or exit exist, no participant abuses market power to set prices and equal access to production technology is provided (Debreu, 1972). Projection of this view of perfect market would mean that an ideal market for electricity must provide a platform that is spatially homogeneous in terms of pricing, in order to allow for the entrance and exit of traded power with the same price. However, since electricity flows according to Kirchhoff's laws, and the flow can be constrained by cable flow capacities, the free flow of traded power may be hindered. This is usually overlooked by the scholars who employ a purely economic perspective. Instead of utilizing the cheapest power, more expensive power has to be utilized in order to satisfy demand due to transmission capacity constraints. As a result some price differences between the nodes occur. This is frequently referred to as congestion cost. The different prices, caused by spatial heterogeneity, are called locational marginal prices (LMP) or nodal prices in the literature. An elaborated explanation of LMP and its relation to transmission congestion is discussed later in this chapter.

The management of congestion implies different results for the efficiency of the generation market. Hence different mechanisms for congestion management have been suggested to allocate scarce transmission and to maintain a competitive market. Some methods are more focused on preventive measures, since they try to avoid the congestion beforehand, while others attempt to solve the congestion in real time. The methods used are dependent on the evolution of the institutional setting within the respective region because of the different paces of development in different parts of Europe.

Some points must be taken into account while considering market mechanisms for congestion management. First of all, it should be noted that the transmission operator is a natural monopoly andto secure the public interest always has a pivotal position. The network operator cannot be relied upon to secure public interest without regulation. The regulation applied to TSO is crucial with respect to market power concerns. Second, it should be realized that supply and demand varies instantaneously, while the market clearance must occur at all times. This may result in volatility, since the demand as well as the supply might be volatile due to many factors. Third, it is important to note that the configuration of the physical network causes network externalities called loop flows. Transportation of electricity does not occur as in the case of a transportation of a physical good in a classical market. Electricity flows through the least resistant cables from a high voltage to a low voltage level. So, in a hypothetical three-node network, sending power from node A to node B is always affected by the resistance of the lines, including those involving node C.

Whatever the scheme for trading is concerned, the market has to reflect congestion costs to the market participants. This is important from two perspectives – a short term market power perspective and a long term capacity investment perspective. The participants should bear the congestion cost and as a result not be tempted to congest the line. This means, for the sake of price signal, instead of preventive mechanisms, congestion pricing mechanisms should be employed. Also the investors should be given incentives to invest more on capacity expansion.

There are a number of policy options for addressing key management issues such as transmission congestion. The options for state-owned or heavily regulated electricity industries will briefly be discussed. Then the options for liberalized markets will follow. The liberalized markets options focus largely on the concept of transmission rights.

In Figure 6.1, one can see the classification of policy approaches that are discussed in this chapter. The main classification point involves the centrality of the policy mechanisms. Decentralized market-based mechanisms always involve transmission rights, which is shown as the prime mechanism opposite state-owned policy mechanisms. While transmission ownership may vary, financial transmission rights are dominated by the locational marginal pricing concept, as will be discussed in the following sections.

6.2.1 State-owned and centrally regulated policies

In this regime, the network is centrally designed, implemented and governed. The vertically integrated monopolist, which is virtually a government organization, controls the whole supply chain. This used to be the predominant regime before the liberalization trend that was mentioned in Chapters 1 and 2. The principal concern with this regime is that there is insufficient information about the state of the system for effective governance. This results in the inefficient allocation of resources to meet consumer demand. A further prob-

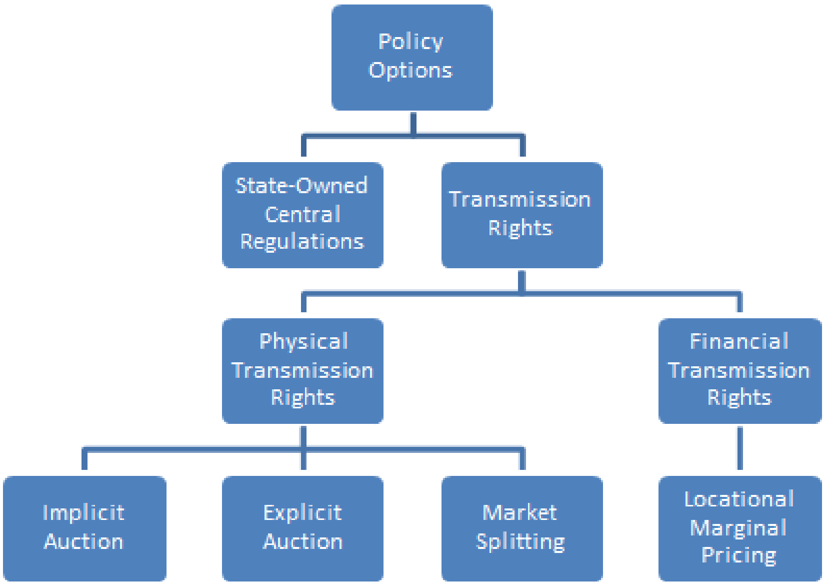


Figure 6.1: Classification of policy options

lem of state-owned industries is that they are subject to issues of political commitment and therefore hold-up. The resultant lack of credibility for sustained support of infrastructure damages confidence in the system.

There are several approaches for managing centrally regulated industries. Cost-plus regulation places infrastructure management in the hands of the private sector, affording the infrastructure supplier a fixed rate of return above and beyond the costs required for infrastructure operation. A drawback of this approach is that it requires a high level of transparency concerning the operating costs of the industry. A second drawback is that the cost plus incentive results in an under-investment in network capacity.

Looser still are virtual competition and benchmark schemes. These schemes further decentralize the network into regional centers of ownership. The networks are placed into virtual competition with one another via a benchmark scheme. Each regional network is given a set of performance targets in terms of network inputs and network deliverables. The best-in-class networks, by any combination of input or output metrics, are guaranteed a fixed rate of return. Other networks are compared directly with these best-in-class operators, and given a correspondingly diminished rate of support according to their performance. Virtual comparators can also be introduced by combining best-in-class operators. The drawback of this approach is that it permits over-investment in infrastructure as a profit-making enterprize (Cunningham and Joode, 2012). Furthermore, the approach is subject to collusion between best-in-class operators. Next the options for a more liberalized market, which involve managing physical or financial transmission rights, is discussed.

6.2.2 Transmission rights

In the European context, the lines that have been congested have traditionally been those on interconnectors that accomplish the connection between neighboring countries. Power generation, as well as transmission and distribution, used to be operated by the national monopolies, and interconnecting lines were used for mostly stability purposes rather than mass energy trade. As the liberalization has taken place, these interconnectors have been increasingly utilized. For example, in 1978 the amount of exchanged energy among UCTE members was 62.9 TWh or 6.2% of the total consumption in the area, whereas in 2008 this number was up tp 285.2 TWh, constituting 11% of the total consumption (Book, 2008). This process resulted in congestion problems in electricity transmission, which occur especially on the international interconnector lines. As a response, transmission congestion management has become a priority on the agendas of regulators. After the liberalization of vertically integrated utilities, transmission system operators (TSO) have taken on the caretaker role of the utility, assuring that the transmission capacity limits are not exceeded.

Congestion management should ideally be done in a strategy-proof fashion. However, the very existence of congested lines causes economic inefficiency and strategic behavior, which hinders the economic efficiency of the transmission market. Some initial ideas regarding how to prioritize the generation firms to utilize congestion-prone lines involve different preventive measures. One idea is to permit the longest running firm the right to transmit, which clearly inhibits competition and therefore also the whole purpose of liberalization. Dividing the capacity among the participant firms in proportion to their capacity bids is another immediate idea, which also fails as it leads the firms to overbid their capacity requirements. Proponents of the electricity market opt for a market-based solution approach, rather than a preventive one, given these aforementioned concerns (Boisseleau and de Vries, 2010). In various markets, this solution emerges in the form of some kind of market mechanism involving property rights on the congested lines. Physical transmission rights (PTR) and financial transmission rights (FTR) are highlighted in this regard, which are discussed in the next two sections.

6.3 Physical transmission rights

Physical transmission rights is the traditional method applied in national markets within Europe, such as in the ELSPOT and ELBAS markets of the Scandinavian NordPool market (Spot, 2011), the APX-ENDEX in the Netherlands and the UK, OMEL in Spain, etc. These tradable property rights provide exclusive rights to utilize a potentially congested line with no additional cost. The market for PTR determines the price for congestion. A supplier must own a right to transfer its power to the demand side. But having a right does not necessarily imply that the right owner has to inject energy at a node and withdraw at another node, unless a UIOGPI (Use It Or Get Paid for It) rule is in place (Joskow and Tirole, 2000). The investments in capacity expansion would create new PTRs to be served to the market. The problem with this market mechanism is the fact that once the capacity on a congested line is increased, it becomes uncongested, which makes the previously granted rights void. This hinders the investment mechanism for capacity expansion. Various market mechanisms in different forms of auctions are discussed and applied in various electricity transmission markets. Three of them are worth mentioning at this point: explicit auctions, implicit auctions and market splitting.

6.3.1 Explicit auction

In this scheme, the auction for capacity doen separately from electricity. Explicit auctions are the simplest method for allocation. Different time horizons can be applied to various markets. Explicit auction poses a cumbersome mechanism in the sense that participants have to join two separate auctions. In addition, the lack of information between two auctions may lead to inefficiency.

The advantage of explicit auction is the ability to trade even if there is no spot market on either side of the congested lines. This type of auction is applied most often to interconnectors between different countries and is prone to fade away as the liberalization blossoms. The NorNed auction for the interconnector between the Netherlands and Norway and the capacity auctions on the Spain-Portugal interconnector are some examples of explicit auctions that are currently in place.

6.3.2 Implicit auction

In implicit auctions, capacity and electricity are not traded in separate auctions. Instead all participants enter the same auction. Those bids for using the interconnector that match are taken to a separate pool. The operator adds a precise fee to the bid price to match the interconnector capacity. This amount is listed as the congestion price settled by the market. Since this process involves only one auction, the expected liquidity is much higher than in explicit auctions. The simpler process for market participants makes it more attractive. The congestion costs are collected by TSO and give a signal of the marginal value of capacity expansion. However, for this method to be applied, there needs to be an exchange operating on both sides of the congested line.

6.3.3 Market splitting

Market splitting is a kind of implicit auction that is also promoted for a pan-European integrated electricity market by European Network of Transmission System Operators (ENTSO). Capacity allocation is based on the bids given by the participants. The markets on the two sides of a congested line are cleared separately, as if there were no connection between the regions. This may result in distinct locational marginal prices. Then the cross border capacity is utilized by the TSOs such that the TSO of the higher priced area buys electricity from the TSO of the lower priced area at the low price. Then it sells the procured electricity in its zone at the higher price, resulting in a net profit for the TSO. This transaction results in a price decrease in the high priced region and a price increase in the lower priced region to minimize the price difference between two areas. For market splitting to be usable, both sides of the congested line must have a market mechanism. It is actively in use in Scandinavian Nord Pool markets. As the various markets within Europe grow more liquid, it is envisaged to be used Europe-wide in the future.

These techniques previously mentioned are known as congestion pricing methods. Apart from those, another set of methods exists which includes corrective methods such as redispatching and counter trading. These methods do not directly affect the prices due to congestion but delegate the responsibility solely to TSOs. Although they are useful in a sense – to incentivize TSO's for capacity expansion – they are not preferable, as they do not give the congestion signal to the market and thus tend to encourage strategic behavior (Knops et al., 2011).

6.4 Financial transmission rights

An alternative mechanism to physical transmission rights is financial transmission rights (FTR). FTR is a hedging tool against congestion charges for markets that are based on locational marginal pricing (LMP). Thus LMP, or nodal pricing, is the prime mechanism on which FTRs are built. It has been applied in the electricity networks of New York, PJM and New England regions in the US (Hogan, 1992). Since LMP is the underlying mechanism that brings about the need for FTRs, in this sections LMP together with FTR are elaborated on. Then the functionality of FTRs is explained. Finally, in the next section, the strategy-proneness of FTR is tested in a game theoretical model.

6.4.1 Locational marginal pricing and financial transmission rights

LMP is the spatial pricing of electricity in which different price zones are formed based on occurrences of transmission congestion on the electricity transmission lines. The electricity prices resulting at each node are called locational marginal prices. In a fully connected network, LMPs on different nodes may end up with different values even if only one transmission line is congested throughout the network. Due to Kirchoff laws, injection and withdrawal of electricity at any node possibly affects the electricity load on any transmission line (Green and Newbery, 1992; Hogan, 1992; Oruç and Cunningham, 2012; Oruç and Cunningham, 2011; Rudnick et al., 1995; Schweppe, 1988).

With FTR model, the TSO computes the LMP for each congestion-prone node, which carries the associated congestion costs. This results in volatile prices in electricity as the congested lines fragment the markets spatially into minor regions. To hedge these volatilities the generation companies can buy FTRs offered by the TSOs. The FTRs entitle the holder to receive the price difference between two stated nodes on the FTR. FTRs are funded by the congestion rent collected by the TSO.

FTRs are utilized as a hedge against the congestion costs due to different LMPs on the generation and consumption nodes. The price differences across the nodes may result in unexpected costs due to the foreseen or unforeseen congestion occurrences. In a nutshell this can be described quantitatively as follows:

Assuming a three-node system, as in Figure 6.2, a firm *Firm 1* at node one (N_1) selling Q_{12} MW electricity to a consumer at N_2 would be paid €p_2Q_{12} , whereas that amount of electricity would be worth €p_1Q_{12} in the originating node. In a situation where $p_1 > p_2$, a net loss of €$(p_1 - p_2)Q_{12}$ to the generation firm occurs. On the other hand, possessing an FTR of Q_{12} MW from $N1$ to $N2$ can provide full protection against such price volatility caused by congestion. Regardless of the congestion situation the generation firm can shield its account from congestion cost. Hence, with an FTR designating $T_{F1,12} = Q_{12}$ amount of power from source node N_1 to sink node N_2 the FTR holder is paid €$(p_2 - p_1)Q_{12}$.

The FTR holders are not required to transfer electricity in order to benefit from the

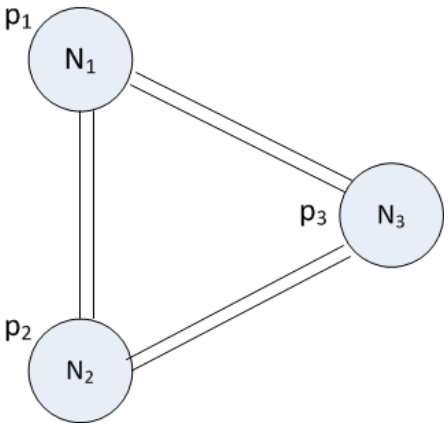


Figure 6.2: Example: A three-node system

awarded credit unlike the alternative transmission capacity allocation methods (Manual, 2008). The fact that FTRs are independently traded enables the transmission system operator (TSO), or independent system operator (ISO) in US context, dispatch generators solely according to the technical limitations but not constrained by capacity allocations. However, for the auction of FTRs a simultaneous feasibility check has to be carried out, which will be explained later. The transmission congestion charges resulting from the congestion after electricity markets (e.g., day ahead markets or bilateral power markets) are used to honor FTRs.

Each FTR is characterized by three attributes, i.e., the path of the FTR rules, designated direction of power flow and the amount of electricity that it corresponds to. The price is determined by the electricity market in the form of LMPs as explained above. The different prices across the transmission path result in a payment to or from the FTR holder. The resulting credit is calculated based on the quantity of electricity the FTR corresponds to and the difference between the respective LMPs.

A prominent theoretical modeling work regarding electricity transmission rights and electricity restructuring was conducted by Hogan (1992) in *Contract Networks for Electric Power Transmission* in which he develops the theory behind transmission rights. Hogan also developed the idea of using path dependent flow based contracts. Joskow and Tirole (2000) made another contribution to the conceptual basis of the current model, taking both physical and financial rights into account. A formal model for the wholesale electricity market was defined and different congestion management methods were applied. No rights, physical rights and financial rights are compared and contrasted, market power concerns are dealt. Furthermore, an elaborated general discussion regarding the financial transmission rights and market power can be found in (Kristiansen, 2004). The following example is intended to clarify the concept of LMP and demonstrate the use of financial transmission rights.

6.4.2 An illustrative example

In Figure 6.3 a three-node example is provided for clarification.

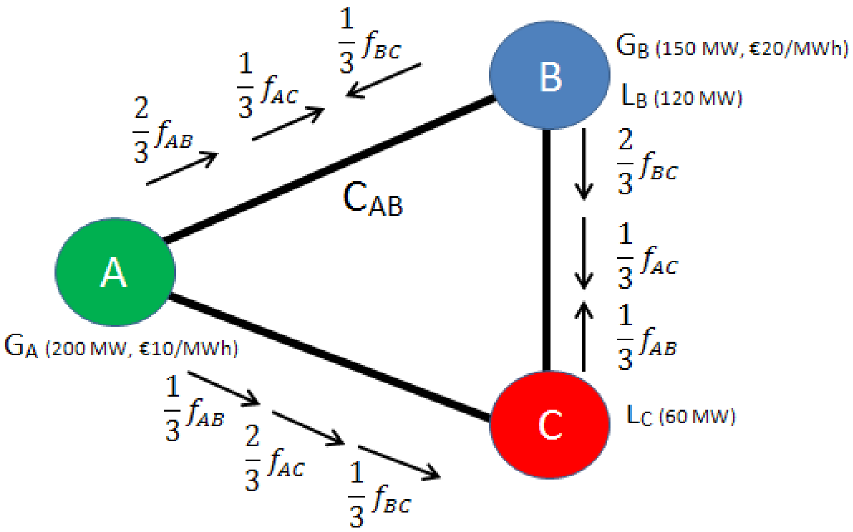


Figure 6.3: Three-node LMP example

Classically, generation costs are determined according to operating costs and unit availability. If congestion occurs, transmission is dispatched and transmission costs are socialized. However, in the case of LMP, generators offer bidding price and all the customers pay the LMP at their respective location (node). In effect, transmission costs are directly assigned to the customers in the downstream of the congested line.

Nodes A and B each contains one generator, respectively G_A and G_B. The maximum amount of electricity generation in terms of MWs and bidding price for each unit of electricity in terms of €/MWh characterizes the generators. Similarly nodes B and C each contains loads, L_B and L_C, measured in terms of MWs. Here the term ‘node’ specifies a spatially proximal generation, demand and transmission facilities, such as a city or a closely integrated region. Within a node, impedance is assumed to be zero, and a generator within a node can supply a load without any impact on the transmission system. In this example system, it is assumed that the transmission lines connecting each node to the others have the same impedance value. Effectively, according to Kirchhoff’s laws, two-thirds of a net flow from node A to node B, i.e., f_{AB}, flow through $line_{AB}$ and the rest flows through $line_{AC}$ and $line_{CB}$. For the critical line, $line_{AB}$, the total flow can be written as:

$$line_{AB} = \frac{2}{3}f_{AB} + \frac{1}{3}f_{AC} - \frac{1}{3}f_{BC} \tag{6.1}$$

The resultant flows and their direction for each line are also depicted in the Figure. Although the transmission lines are assumed to be identical in terms of impedance values, a capacity constraint, i.e., C_{AC}, is attained only for the line between node A and node B. The other lines’ capacity constraints are not interesting for illustrative purpose and are hence assumed to be infinite.

Case 1: $C_{AB} = \infty$

Let us firstly consider the system in Figure 6.3 without transmission capacity constraint, i.e., $C_{AB} = \infty$. In this case the economical dispatch occurs in which the generators are operated by merit order, that is, first G_A is operator and then G_B. The total load of 180 MW is satisfied by G_A, which has a total capacity of 200 MW. In this case the expensive generator at node B is not operated at all. LMP's are determined according to the marginal system cost caused by one more hypothetical MW at the corresponding node. In this example since the next MW of load at any node is satisfied by the same generator, i.e., G_A, LMP at all nodes is identical, namely 10/MWh. In general, if a system is unconstrained then LMP at every node is identical. As a result, the line connecting node A and B carries $2/3 f_{AB} + 1/3 f_{AC} = 100$ MW of power according to Equation (6.1).

In this case, the total payment to production is 180 MW x10/MWh=€1800 per hour, which is equal to the collections from load demanding entities that is 120 MW x10/MWh+ 60MWx10/MWh= €1800 per hour.

Case 2: $C_{AB} = 80$ MW

Second, suppose this system is constrained by a transmission capacity of $C_{AB} = 80$ MW on the line connecting node A and B. At this point the TSO's duty is to find the most economical dispatch and ordering the generators to power up the system accordingly. This is done centrally with the help of software based on state of the art optimization methods. However, in this example it is feasible to calculate economical dispatch manually. Since the load on $line_{AB}$ carries 20 MW less than unconstrained case, a part of L_B is satisfied by G_B. By considering Equation (6.1) one may easily derive that GB satisfies 30 MW of LB, whereas G_A satisfies 90 MW of L_B and 60 MW of L_C. As a result, LMP at node B becomes 20/MWh as the next MW demand at node B is satisfied purely by G_B, whereas LMP at node A stays as 10/MWh. On the other hand, the next MW demanded at node C would be satisfied by both G_A and G_B since a sole G_A production would infringe capacity constraint on $line_{AB}$.

The total marginal production by the generators can be written as:

$$\Delta G_A + \Delta G_B = 1 \tag{6.2}$$

If one considers Equation 1, the net flow through $line_{AB}$ caused by the marginal productions to node C is zero as long as the following equation is satisfied;

$$\frac{1}{3}\Delta G_A + \frac{1}{3}(-\Delta G_B) = 0 \tag{6.3}$$

Solving Equation (6.2) and Equation (6.3) together one may find $\Delta G_A = 1/2$ and $\Delta G_B = 1/2$. As a result, the LMP at node C is found as €15/MWh in this example.

In this case, the payment to generation companies can be calculated as 150MWx10/MWh +30MWx20/MWh=€2100 per hour, whereas the collected payments from the load-serving entities is 120MWx20/MWh+60MWx15/MWh=€3300 per hour. The overpayment of €1200 per hour is caused by the capacity on $line_{AB}$. Transmission congestion is created by such a constraint, when the economic dispatch dictates overcapacity utilization. As a result, a more expensive generator (i.e., G_B in this example) is utilized to satisfy the excessive load (i.e., a part of L_B in the example).

The consequence of this is that the generation companies upstream of a congested line receive a lower price than the generation companies on the downstream side. The difference between the downstream and upstream sides of congested line determines the congestion price. Those firms having an FTR for this particular congested line collect this congestion price. Hence, having the respective FTR with the amount of transmitted MWs it permits over this line, a upstream generator collects the same amount of money as the downstream generators.

6.4.3 Obligations and option FTRs

An FTR reserves a designated amount of virtual capacity on the respective transmission line. The hourly economic value of a particular FTR is determined by the LMP difference between two nodes the transmission line is connecting. This difference is not quantified as an absolute value but as the difference between the sink node and source node that are defined by the FTR. Eventually, the resulting value can be a liability as well as a benefit, depending on the direction of flow that the FTR designates. The hourly economic value of an FTR is positive if the designated flow the FTR represents is in the same direction as the congestion flow, which means that the LMP at the sink node is greater than the LMP at the source node. Similarly if the LMP at the source node is greater than the LMP at the sink node (i.e., congestion is in the counter direction to the flow FTR designates), then the economic value is negative, which imposes a liability to the FTR holder. However, note that if the FTR holder indeed transmits the virtually reserved energy through the respective line, it can earn from congestion rent as much as it loses due to the liability that FTR imposes. This type of FTR is called ‘obligations’ in financial terms. Obligatioons are used to characterize one particular kind of FTR. The payoff for obligation FTRs can be characterized as follows:

$$P_{f,ij} = T^{b}_{f,ij}(p_j - p_i) \tag{6.4}$$

where f denotes the FTR holder firm, b the obligation kind, T the designated capacity, p_i the LMP at node i and ij the source and sink nodes respectively. In this model FTR direction can be noticed from node order ij. Thus the following property holds:

$$T^{b}_{f,ij} = -T^{b}_{f,ji} \tag{6.5}$$

As opposed to the obligation definition made above, a second kind of FTR, namely FTR option, can be defined. In such a scheme, the holder has the right to choose when to exercise the FTR, resulting in an effective FTR when it is a benefit and in a non-effective FTR when it is a liability. The hourly economic value of an FTR option becomes positive when the line designated to the FTR is congested in the same direction, that is the sink LMP is greater than the source LMP just as in obligation FTR. However, its hourly economic value is zero when source LMP is greater than the sink LMP contrary to the obligation FTR. Because of the fact that options are superior in terms of payoff, they tend to be priced higher than obligation FTRs. In practice, limits of some transmission lines maybe forced towards either direction seasonally throughout the year. Consequently, the payoff for option FTR is formalized as;

$$P_{f,ij} = |T^{p}_{f,ij}| max\{(p_j - p_i), 0\} \tag{6.6}$$

where *f* denotes the FTR holder firm, *p* option type, *T* the designated capacity, p_i the LMP at node *i* and *ij* the source and sink nodes respectively. Coexistence of both kinds of FTRs in FTR markets is agreed to produce better results as the plurality of options is considered to create flexibility of transmission markets (O'Neill et al., 2002). However, in this study only FTR obligations are assumed.

6.5 Coupled electricity-FTR market model

FTRs were originally designed as a hedging mechanism against congestion costs. It remains to be proven, however, whether financial transmission rights may also be used as a remedy against excessive market power. An early proposition by Oren (1997) states that financial transmission rights will have no value in the presence of market power. Stoft (1997) refutes this claim through formal modeling of the trade of rights. His results bear the important caveat that there must be excess generation capacity, or else the shadow price of additional transmission capacity is necessarily zero. Kristiansen and Rosellón (2006) take the practical argument still further by proposing a merchant mechanism which fully incentivizes long-term expansion while still being incentive compatible given realistic preferences on the part of the investor.

In this section a simulation model is formulated, which is used to test strategic hypotheses. The model is comprised of two parts that represent two coupled markets, i.e., electricity market and FTR market. Equilibrium models for power networks, although underemphasized, have been an active research field. In most of these, Cournot based competition models, in which firms compete based on quantities they produce, are placed at the core of the analysis.

Power network modeling has been utilized in many applications such as electricity pricing, risk management and market power analysis. More recently, FTR market models have been addressed by various researchers (Berry et al., 1999; Hobbs, 2001; Hogan, 2002; Joskow and Tirole, 2000; O'Neill et al., 2002).

The model proposed in this chapter is a coupled electricity and FTR market model. It features both the FTR market and the electricity market, which are coupled by the decisions of the electricity firms and the price signals that affect each market recursively. Most of the models readily available in the literature are based on assumed LMPs, thus ignoring the electricity market part of the mechanism or are based on stochastic FTR values in conjunction with the electricity equilibrium models. However, the existence of two distinct market structures, the signals of which affect each other, is a more accurate view of the total system. This is the perspective that is employed in this research.

One specific strategic hypothesis to be tested in this analysis can be formulated as follows: "Can firms exercise market power in electricity markets by keeping their generation information private?" This question requires us to consider the market power of the firms in the electricity market and amount of FTRs they can acquire. Moreover two markets are interrelated as the evaluation of FTRs depend on the results of the electricity market. To test strategic hypotheses such as the one stated here, one needs to model the electricity market as well as the FTR market.

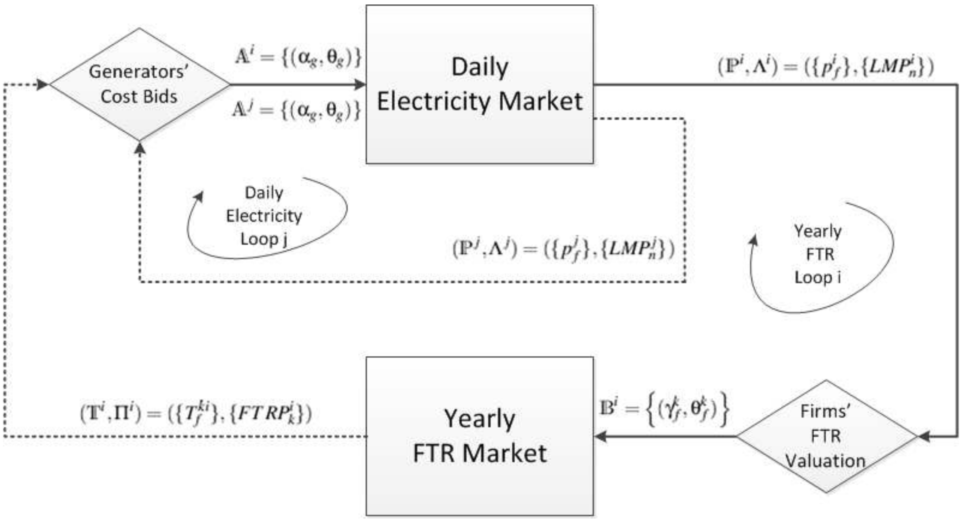


Figure 6.4: Coupled FTR and Electricity Market

In Figure 6.4 the process flow of the model is depicted. The algorithm processes the FTR market and the electricity market recursively. In general, electricity wholesale markets are organized as daily day-ahead markets. The electricity is priced daily based on the forecast of the price settlement of the next day. In the figure, daily electricity loop, which is indexed with j, is shown to run recursively. This market involves a general equilibrium model, which is run by the Transmission System Operator (TSO). This equilibrium is the Nash equilibrium in game theoretical terms. At the equilibrium point, the prices of electricity at each node in the system (i.e., LMPs) are determined. In the figure, the set of these prices is denoted as Λ^j, and the set of allocations of power generation is denoted as $\mathbb{P}^j$. Furthermore, the derivation of these sets is shown in Section 6.5.1.

At the end of a given year, the FTR market is run in parallel to the electricity market. The price and allocation of electricity throughout the previous years are observed to forecast the next year's electricity price and allocation, as depicted in Figure 6.5. Accordingly the firms evaluate the FTR prices and submit an *FTR market valuation set*, i.e., $\mathbb{B}^i$, to the FTR market based on the price and allocations of the previous year $\mathbb{P}^i$ and Λ^i. The yearly FTR market is run based on the FTR market valuation set and involves another uniform auction and a corresponding optimization problem, the details of which are discussed in Section 6.5.2. Accordingly, FTR allocations, $\mathbb{T}^i$, and the prices of FTRs, Π^i, are settled, as is the output to the generators. The FTR market allocations may affect generator bids in electricity market.

The model presented here is consistent with real-life situations given the typical market cycle durations for electricity and FTR markets. FTRs in real-life are typically run in longer terms (e.g., monthly, annual and longer term in PJM market or ERCOT market) whereas electricity wholesale markets are typically held in shorter terms (e.g., daily basis in PJM or NordSpot).

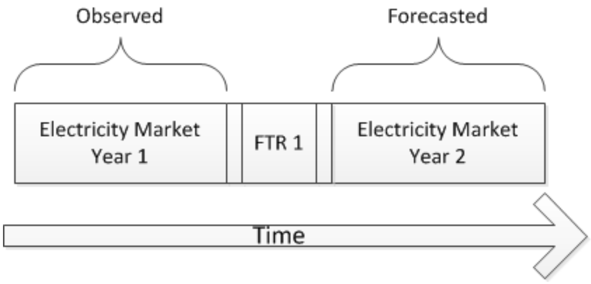


Figure 6.5: Flow of Electricity-FTR market simulation

In this simulation, which is explained further in the following sections, it is assumed that the daily market to be deterministic, hence, simulated only once. No stochasticity is assumed, thus, no variations in daily conditions exist in order to not complicate the model. Hence, the daily market is run once and the results are passed on to the firms for FTR valuation.

Furthermore, generator firms are assumed to be price-takers and they offer their electricity at their marginal costs. In real-life, such firms may consider submitting false cost functions based on the FTR market results and the daily market results. There are various models in the literature that investigate the bidding behavior in the electricity market and leverage FTR for strategic benefit. For a vivid example of such behavior, one may see the three-node, four firms example in (Rourke et al., 2003), where a generation firm that happens to be present in two different nodes bids strategically to create and benefit from a congestion.

Thus the flow chain of the simulation model that is explained in the following sections does not involve the dotted links in Figure 6.4. As shown in Figure 6.5 the simulation model starts with the electricity market, which is followed by an FTR market and then the next year's electricity market.

6.5.1 Electricity market

In this model, the electricity market is composed of the generation companies, the load-serving companies (typically electricity retailers) and the transmission system operator (TSO). The term 'node firm' is used as a collective term for the generation companies and the load-serving companies at a particular node. The notion of node firm may correspond to various real-life entities. It may mean a particular firm that has various generators at a particular node or it may mean multiple companies that dispatch or demand electricity in one particular node. The firms at a node are not discriminated with each other. Rather, the collective node firm concept is used for the sake of notation simplicity and conceptual understanding.

The generation capacities offered by the firms at a particular node are collected by the TSO and ordered according to merit. This results in a supply function that is offered by the particular node generator. Similarly a demand function is obtained for each node load. Thus, each node has at most one node generator and one node load. The term 'node firm' can indicate both types of firms.

Assume there are $|\mathbb{F}|$ number of firms participating in the market, where the cardinality of the set $\mathbb{F}$ denotes the set of the participating firms. The set of participating firms are composed of the load-serving entities (the set of which is denoted by $\mathbb{L}$) and generator firms (the set of which is denoted by $\mathbb{G}$). Hence, $\mathbb{F} = \mathbb{L} \cup \mathbb{G}$ can be written.

In this model $k \in \mathbb{K}$ denotes a power line, the capacity of which is sold on the FTR market. There is a certain load capacity associated with each power line. Since the electricity wires can carry electricity in both directions, the direction of flow should also be denoted mathematically. k^+ denotes one direction whereas k^- denotes the opposite direction in this model. For the sake of readability, k is used in place of k^* (i.e., either k^+ or k^-) for the rest of this manuscript and treat k^+ and k^- as two different links when this is needed. The directions are imperative only at the constraint satisfaction level.

Generator node's supply function

Each node generator offers a supply curve as in Figure 6.6, as explained earlier with Figure 5.6 in Chapter 5. Each generator bids are ordered from least costly to most costly. At the intersection with the demand curve, the operating point is settled.

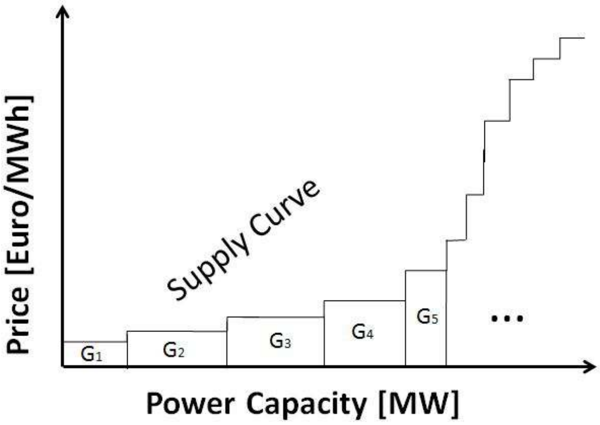


Figure 6.6: Merit-ordered electricity supply by node generator *at a particular node*

The following convex logarithmic function represents supply curve in this model.

$$f(P) = \begin{cases} -\beta \log \frac{\alpha - P}{\alpha} & \text{if } \alpha > P > 0 \\ \infty & \text{if } P \geq \alpha \\ 0 & \text{otherwise.} \end{cases} \tag{6.7}$$

The function is depicted in Figure 6.7 for an arbitrary α, β pair (i.e., $(\alpha, \beta) = (900, 10)$). This function has the following merits: 1) it captures the dramatic increase of the marginal price; 2) it limits the maximum possible output of the generators because of the asymptotic behavior.

Thus the *Cost Bid* of a particular generator g is determined by:

$$A_g = (\alpha_g, \theta_g) \tag{6.8}$$

And the total *Cost Bid* set as depicted in Figure 6.4 is passed on to the electricity market.

$$\mathbb{A}^i = \{(\alpha_g, \theta_g)\} = \{A_g^i\} \quad \forall g \in \mathbb{G} \tag{6.9}$$

The generator gives a decision at this point. It may submit the true generation values or it may opt for submitting cost functions strategically. There are various studies that scrutinize generation values. However, it is not the intention of this research to work out this behavior in this research. Hence, the decision at this point to be made is assumed to be based on the true cost of the electricity and that it does not depend on the FTR market output or any strategic intention.

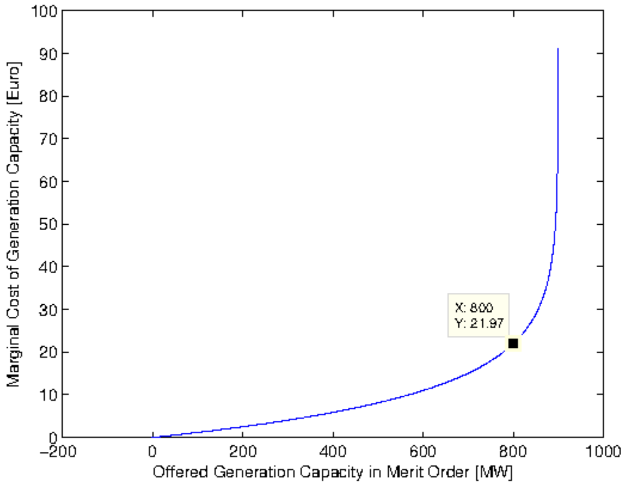


Figure 6.7: Merit-ordered electricity supply function in the model

Load node's demand function

Each load node produces an inelastic linear electricity demand function. This demand is assumed to be fixed, hence, totally inelastic. p_d symbolizes the power demand of a particular load node d's power demand. p_d is assumed to be always negative and implies a negative PTDF (Power Transmission Distribution Factor), which will be explained in the following section.

Power flow allocation problem

After the TSO receives generation bids, the market is settled by it. Today's energy markets predominantly use optimal power flow (OPF) algorithms to settle the market. Various algorithms are suggested in the literature and used in practice (Huneault and Galiana, 1991; Stern et al., 2006). The main difference among these OPF algorithms is the choice of objective function and AC and DC trade-offs. A DC estimation is used, i.e., a DC model (Wood and Wollenberg, 2012), in this simulation for the sake of simplicity. In this analysis total cost of the consumed electricity is assumed as the objective function for electricity allocation. Using the conceptual function in (6.10), the cost function of a particular generator $g \in \mathbb{G}$ can be written as;

$$C_g(p_g) = \begin{cases} -\beta \log \frac{\alpha_g - p_g}{\alpha_g} & \text{if } \alpha_g > p_g > 0 \\ \infty & \text{if } p_g \geq \alpha \\ 0 & \text{otherwise.} \end{cases} \tag{6.10}$$

The TSO allocates the generation tasks such that the total cost of production, $\sum C_g(p_g)p_g$, is minimized in the following optimization problem:

$$\begin{aligned} \min_{p_g} \quad & \sum_{g \in \mathbb{G}} C_g(p_g)p_g && && (6.11) \\ \text{s.t.} \quad & \sum_{f \in \mathbb{F}} p_f = 0 && , \quad \forall f \in \mathbb{F} = \mathbb{G} \cup \mathbb{L} && (6.12) \\ & \left| \sum_{f \in \mathbb{F}} \eta_k^{fh} \, p_f \right| \leq c_k && , \quad \forall k \in \mathbb{K} && (6.13) \\ & p_f \geq 0 && , \quad \forall f \in \mathbb{G} && (6.14) \end{aligned}$$

The control variables are the electricity supply, p_f of each generator in this optimization problem. The electricity demand of each load-serving entity, i.e., p_g is assumed to be constant and given.

Constraint (6.12) is the condition for energy balance. The total dispatched power must be equal to the total load in the system, whereas the condition (6.14) makes sure that the load and supply of electricity is greater than zero at all times.

The inequality (6.13) enforces the capacity load on each electricity line to be less than the physical capacity of the respective line. In this inequality p_f is the electricity supply or demand of each firm in the network, i.e., supply for a generator and demand for a load-serving entity. η_k^{fg} is the 'power transfer distribution factor' (PTDF) of the power injected from the firm f to g (thus, from the corresponding node where f resides, to the node where g is situated) on the link k.

In this formulation, a 'hub-node' is assumed, which is an arbitrary node chosen by the algorithm, and all the power flow is assumed to be cross-transferred over this node. This assumption is made to be able to calculate the PTDFs as a PTDF calculation is employed that is based on power flows between corresponding two nodes. In equation (6.13), h corresponds to this hub node. The choice of hub node does not change the resulting locational marginal prices or the power flows. The power supply of each generator is used as the control variable and use PTDFs to determine the electricity flows on each link, which are kept lower than the link capacities by (6.13).

Calculation of power transfer distribution factors (PTDF)

In general, due to the nature of electricity, an intended power transfer from one node to another does not totally flow on a single line. The electricity always flow in parallel lines. This property of the electricity is governed by the Kirchoff laws. As a result of this property, various proportions of the intended power transfer flow over different lines. Power transfer distribution factors (PTDF) denote the proportion of an intended power flow over each of the power lines in the network.

PTDFs were discussed previously in Section 6.4.2. Consider Figure 6.3 in this section. As seen in the figure, for an intended flow, f_{AB} from *NodeA* to *NodeB*, $\frac{2}{3}$ of the intended power flows through $Line_{AB}$ and $\frac{1}{3}$ of it flows first through $Line_{AC}$ and then $Line_{CB}$. Hence, for this specific network one may write the following PTDFs: $\eta^{AB}_{AB} = \frac{2}{3}$, $\eta^{AB}_{AC} = \frac{1}{3}$, $\eta^{AB}_{BC} = -\frac{1}{3}$. The last fraction is negative since we consider $Line_{BC}$ but not $Line_{CB}$.

PTDFs are calculated based on the line reactances and network configuration. Exact calculations of PTDFs may vary. Christie et al. (2000) formulate DC power flow in terms of electricity phase angles. The reactance matrix that relates the power flows with the reactance of each link is used to calculate PTDFs. According to DC power flow assumptions that are further explained in (Christie et al., 2000) the power flow from node *n* to *m* is represented as:

$$p_{nm} = \frac{1}{x_{ij}}(\theta_n - \theta_m) \tag{6.15}$$

Then the total power supply of a particular node *n* can be expressed as

$$p_m = \sum_m p_{nm} \tag{6.16}$$

Taking all the nodes into account, in matrix form, the following equation holds;

$$\begin{bmatrix} p_1 \\ \vdots \\ p_n \end{bmatrix} = B_x \begin{bmatrix} \theta_1 \\ \vdots \\ \theta_n \end{bmatrix} \tag{6.17}$$

where B_x is the susceptance matrix of the network which is found by using reciprocals of line reactances. Inverting the susceptance matrix, one can find the reactance matrix X.

$$\begin{bmatrix} \theta_1 \\ \vdots \\ \theta_n \end{bmatrix} = X \begin{bmatrix} p_1 \\ \vdots \\ p_n \end{bmatrix} \tag{6.18}$$

The same method as in (Christie et al., 2000) is used to find PTDFs in this algorithm with the following formula:

$$\eta^{nm}_{ij} = \frac{X_{ni} + X_{mj} - X_{nj} - X_{mi}}{x_{ij}} \tag{6.19}$$

Here η^{nm}_{ij} represents the PTDF of a power transfer from node *n* to *m* on the transfer line from *i* to *j*. X_{ni} is the corresponding entry in reactance matrix *X* for a power transfer from node n to m on the ij link.

Calculation of locational marginal prices (LMP)

Locational Marginal Prices are calculated based on the optimization problem in (6.11)-(6.14). There exist one equality constraint and two inequality constraints for each line (for two possible directions of flow) in the problem. Thus the lagrangian function of the optimization problem contains one equality multiplier and 2 x $|\mathbb{K}|$ inequality multipliers;

$$\mathcal{L}(p_g,\lambda,\mu_k) = C(p_g)p_g - \lambda(\sum_{f\in\mathbb{F}} p_f) - \sum_{k\in\mathbb{K}} \mu_k^+(\sum_{f\in\mathbb{F}} \eta_k^{fh}\, p_f - c_k) - \sum_{k\in\mathbb{K}} \mu_k^-(-\sum_{f\in\mathbb{F}} \eta_k^{fh}\, p_f - c_k) \tag{6.20}$$

The definition of LMP at a particular node n is ‘the increase in the total cost by an marginal increase of load at the respective node n’. Here it is assumed that there a load exists at each node n in the network, where $n \in \mathbb{N}$, the set of all the nodes in the network. Thus we replace p_d in equation (6.20) with p_n. Since the lagrangian in equation (6.20) gives the total cost of generation, we can find the corresponding LMPs for each node by taking partial derivative of the lagrangian function for p_n $\forall n \in \mathbb{N}$, where $\mathbb{N}$ is the set of all nodes in the network. Then the derivative needs to be negated since the demand is defined as a negative value in this notation. Note also that in this notation p_f where $f \in \mathbb{F}$ is composed of both generators p_g and loads p_d (p_n in this case).

$$LMP_n = -\frac{\partial \mathcal{L}(p_g,\lambda,\mu_k)}{\partial p_n} = \lambda + \sum_{k\in\mathbb{K}} \mu_k^+ \eta_k^{nh} - \sum_{k\in\mathbb{K}} \mu_k^- \eta_k^{nh} \tag{6.21}$$

where λ is the equality multiplier and μ_k is the k_{th} inequality multiplier with $+$ and $-$ representing the direction of flow. Also, h is the hub node and k is the k^{th} line of the network as explained before.

λ is the energy component of the LMP price and $\sum_{k\in\mathbb{K}} \mu_k \eta_k^{nh}$ is the congestion component of it. Each inequality multiplier μ_k represents the effect of the marginal load at the k^{th} node on the total price increase. η_k^{nh} represents the PTDF of the energy transfer from the n^{th} node to the hub node on the k^{th} line. The sum of all the induced price increases due to the loading of the lines gives the congestion component of the LMP at the particular node n.

Electricity market output to FTR market

Two sets of values derived from the electricity market are impartial for the FTR market: power allocations and LMPs. These two sets are passed onto the FTR market, as explained by Figure 6.4.

The set of the LMP_n at a certain iteration i constitutes the Λ^i. Similarly the set of the p_f^i at equilibrium constitutes $\mathbb{P}^i$ of the current loop.

$$\mathbb{P}^i = \{p_f^i\} \qquad \forall\, f \,\in\, \mathbb{F} \tag{6.22}$$

$$\Lambda^i = \{LMP_n^i\} \quad \forall\, n \,\in\, \mathbb{N} \tag{6.23}$$

6.5.2 The FTR market

The FTR market is based on the 'FTR valuation functions' of the participating players, i.e., the firms that are interested in capacity on the available transmission links. Each firm in the market submits an FTR valuation function for the transmission lines that are available to it. Since each FTR values the price difference between the sink and source nodes of the corresponding line, this function is naturally governed by the LMP prices that are the outcomes of the electricity market, as explained in the previous section. In addition to the LMP difference between the nodes, a slight drop in value with an increasing number of a given type of FTR is assumed. This assumption is based on the risk-averseness of the firms with an increasing number of FTR.

The decreasing concave FTR valuation function that is assumed here is;

$$f(T) = \gamma - \theta\, T \tag{6.24}$$

where T is the amount of capacity demanded, γ is the price projection of the firm (most often ΔLMP, which is the difference between the projected LMPs at the sink and source nodes) and θ is the risk decrease factor. The function is depicted in Figure 6.8 for $\gamma = 36$ and $\theta = 0.003$.

Let $f \in \mathbb{F}$ be a firm in the market and $k \in \mathbb{K}^f$ be a line that is available to firm f, where $\mathbb{K}^f$ denotes the set of such links. The FTR valuation function $V_f^k(T_f^k)$ of firm f for the link k can be written as;

$$V_f^k(T_f^k) = \gamma_f^k - \theta_f^k T_f^k \tag{6.25}$$

where T_f^k is the decision variable that indicates the amount of capacity that firm f claims on line k. Hence, the (γ_f^k, θ_f^k) pair determine the valuation of firm f for line k with a certain direction, where T_f^k is the amount of capacity demanded for this particular line by firm f.

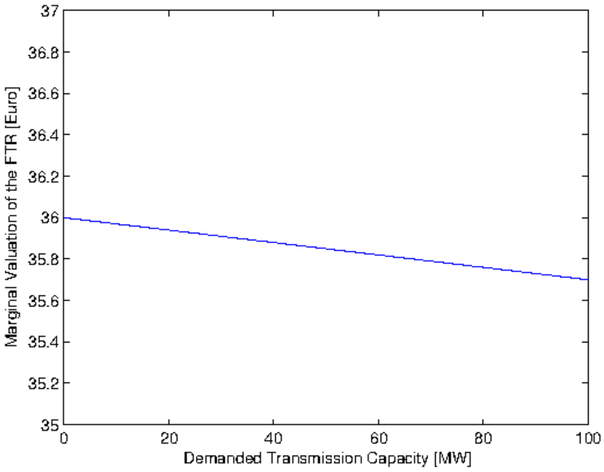


Figure 6.8: Marginal Valuation of Demanded FTR

Then the set of the bids of firm f for all the lines that is available to it determines the 'total firm bid', B_f, of the firm f:

$$B_f = (\gamma_f^k, \theta_f^k) \quad \forall k \in \mathbb{K}^f \tag{6.26}$$

The total set of all firm bids determines the 'total market bid', $\mathbb{B}^i$, at iteration i. This bid set is fed into the FTR market (auction), as illustrated in Figure 6.4.

$$\mathbb{B}^i = \left\{(\gamma_f^k, \theta_f^k)\right\} = \{B_f^i\} \quad \forall f \in \mathbb{F} \tag{6.27}$$

Next, the TSO runs an auction based on the bids of the players and the configuration of the electricity network.

FTR allocation problem

The TSO aims to distribute the limited transmission capacity among the players such that the capacity is allocated to the firm that needs it most. It is assumed that a uniform price auction takes place here, as in the case of the electricity market that was formulated in the previous sections. Distributing the capacity in this fashion results in the correct pricing of the capacities.

The equation (6.25) gives the valuation function for the firm f for a particular FTR T_f^k. The payoff, i.e., the benefit of procuring the amount T_f^k of FTR, would mean the multiplication of this equation with the amount of FTR it has. Hence, the sum of all the payoffs for all the FTRs that firm f has gives the total payoff value for firm f:

$$TV_f(T_f^k) = \sum_{k \in \mathbb{K}} V_f^k(T_f^k) T_f^k, \quad \forall f \in \mathbb{F} \tag{6.28}$$

Accordingly, TSO solves the following optimization problem that maximizes the total payoff of all the FTR market participants:

$$\max_{T_f^k} \quad \sum_{f \in \mathbb{F}} TV_f(T_f^k) T_f^k \tag{6.29}$$

$$\text{s.t.} \quad \left| \sum_{f \in \mathbb{F}} \sum_{l \in \mathbb{K}} \eta_k^l \, T_f^l \right| \leq c_k \quad , \quad \forall k \in \mathbb{K} \tag{6.30}$$

$$T_f^k \geq 0 \quad , \quad \forall f \in \mathbb{F}, \forall k \in \mathbb{K} \tag{6.31}$$

where η_k^l is the power transfer distribution factor (PTDF) of the hypothetical power injected, represented by the FTR T_f^l (from the source to the sink of line l) on the line k. Equation (6.30) guarantees that the sum of the power flow implications of all the FTRs does not infringe upon the capacity constraints of the lines. Note once more that for each k in equations (6.11)-(6.13), we treat two directions (i.e., + and -) separately.

Calculation of FTR prices

The price (i.e., $FTRP_k$) of an FTR (i.e., T_k) for an arbitrary line (i.e., k) is determined in a way similar to that of the derivation of the price of an LMP. The definition of the price of an

FTR at a particular line k is the increase in the total payoff of all the firms with a marginal increase in FTR of a particular line k. Hence, by definition, the prices of the FTRs at the equilibrium point is nothing but the gradient of the objective function in equation (6.29):

$$FTRP_k = \max_f \{\nabla_{T_f^k}(\sum_{k \in \mathbb{K}} V_f^k T_f^k) \quad \forall f \in \mathbb{F}\} \tag{6.32}$$

The gradient of the objective function gives $|\mathbb{F}|$ number of different values for each line k. This is due to the fact that each player bids a different valuation function for a particular line. The maximum among all the gradients is the price of the FTR since the maximum bidder would eventually acquire the next FTR.

FTR market output to electricity market

FTR market allocation determines the price and allocation sets of FTRs, i.e., Π^i and $\mathbb{T}^i$ at a particular instance i, which drives the generator electricity bid as shown in Figure 6.4.

The set of the $FTRP_k$ at the iteration i constitutes the Π^i. Similarly the set of the $T_f^k, \quad \forall f \in \mathbb{F}$ at equilibrium point constitutes $\mathbb{T}^i$ of this instance i.

$$\mathbb{T}^i = \{T_f^{ki}\} \qquad \forall k \in \mathbb{K}, \quad \forall f \in \mathbb{F} \tag{6.33}$$

$$\Pi^i = \{FTRP_k^i\} \quad \forall k \in \mathbb{K} \tag{6.34}$$

The generators decide on which supply functions they provide for the electricity market based on the FTR market values as well as the cost of the electricity and the electricity market results.

6.5.3 Numerical example

A mathematical formulation of the coupled electricity and FTR market is provided in the previous section. The application of the mathematical formulation is to be provided in this section.

The system is coded in a custom made Electricity-FTR market workbench using MATLAB. The linear programs are solved numerically using the ‘fmincon’ solver of MATLAB. The original code can be seen in Appendix C. First, a validation example is provided. The purpose is to show a proof of the concept that can be tractable and inspectable without actually coding the algorithms provided. Next, a scenario, an example of an imperfect knowledge game, is formulated and simulated. In this scenario, we will see that the generators can leverage the FTR market based on hidden knowledge.

A validation example

This subsection aims to provide a validation of the above formulated coupled FTR-Electricity model by applying it to a relatively simple system. Joskow and Tirole (2000) were the first authors who examined strategic behavior in electricity markets. In this part, their topology, in which two generators and a load exist, is used. The topology is shown in Figure 6.9.

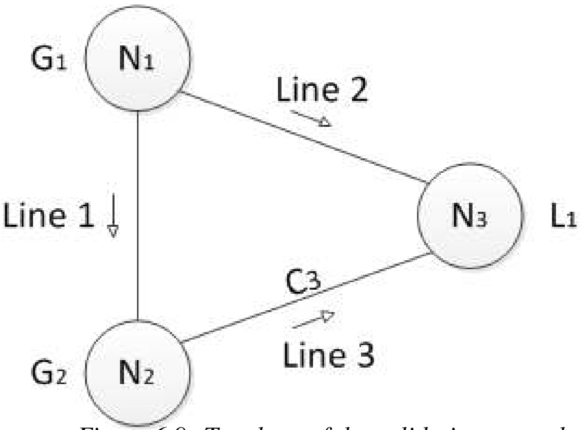


Figure 6.9: Topology of the validation example

There are three components of the system that need to be specified: line characteristics, generator characteristics and load characteristics.

Lines

Line No (k)	From	To	Reactance (x_k)	Link Capacity (c_k)
1	1	2	1 p.u.	10000 MW
2	1	3	1 p.u.	10000 MW
3	2	3	1 p.u.	**50 MW**

Table 6.1: Line characteristics of the example network

In this validation model, equal impedances are assumed, i.e., 1 per unit reactance. Following the topology shown in Figure 6.9, the links of the nodes are specified in Table 6.1. The first column specifies the number of the line in the network. This number also corresponds to the k index in this mathematical formulation. The second and third columns specify the nodes that the line connects. The fourth column specifies the reactance of the lines, which are written in normalized units. The last column shows the line capacities, which are kept high such that no congestion threat exists for the first two lines and remains low for the third one. Given the demand values in this network, congestion is likely to occur on the third line, which is the bottleneck node in this network.

Generators

Generator No (g)	Node (n)	α_g	β_g	Status
1	1	150 MW	€50	1
2	2	150 MW	€30	1

Table 6.2: Generator characteristics of the example network

In Table 6.2 the generator characteristics are listed. The first column shows the order number of the generators, which is denoted as g in this mathematical formulation. The second column shows where each generator resides. The third and forth columns are the α

and β values of the generators as formulated previously. These values determine the supply function of the electricity. The last column specifies whether the generator is active or not (indicated by a value of 1 or 0).

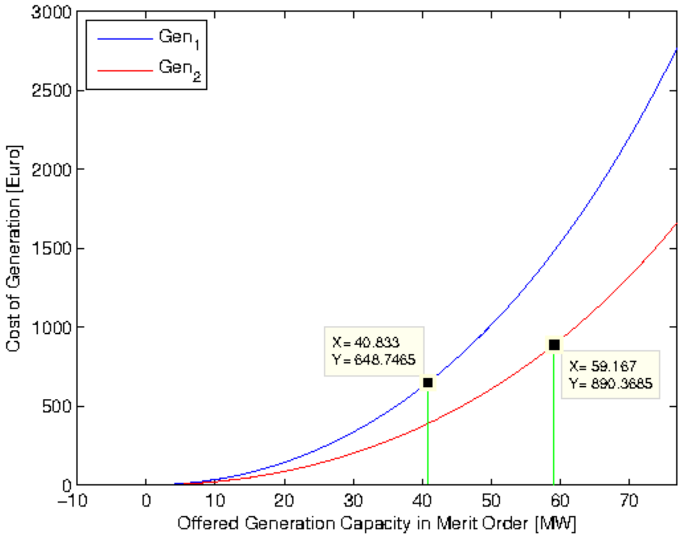


Figure 6.10: Cost of generation for validation example without bottleneck line

In Figure 6.10, one can see the graphical correspondence of the generator values in Table 6.2.

Load

Load No (d)	Node (n)	Demand (p_d)
1	3	100 MW

Table 6.3: Load characteristics of the example network

Table 6.3 lists the load characteristics. There is only one load in this validation example, which is located at the third node with 100 MW of demand.

A) Results for *Line 3 Capacity* = 10,000 MW

For the case where the Line 3 capacity is close to infinity:
The electricity profit is calculated as follows;

$$Electricty\ Profit = Electricty\ Revenue - Electricty\ Cost \tag{6.35}$$

$$Electricty\ Profit = LMP_{ng}\ p_g - C_g(p_g)\ p_g \tag{6.36}$$

where ng is the node at which generator g is located.

Electricity Market Results

LMP		Transmission Loads		Energy Allocations		Electricity Profit	
Node(n)	LMP(€)	Line(k)	t_k(MW)	Gen(g)	p_g(MW)	Gen(g)	R_g(€)
1	34.59	1	-6.11	1	40.83	1	764
2	34.59	2	46.94	2	59.17	2	1156
3	34.59	3	53.06				

FTR Market Results

FTR Prices			FTR Allocations			FTR Profit	
Line(k)	Reward(€)	Price(€)	Gen(f)	Line(k)	T_f^k(MW)	Gen(f)	Profit(€)
1	0	0	1	1	0	1	0
2	0	0		2	0	2	0
3	0	0		3	0	Total Profit	
			2	1	0	1	764
				2	0	2	1156
				3	0		

Table 6.4: Electricity-FTR market results for validation example with no capacity limit

Similarly FTR profit is calculated as follows;

$$FTR\,Profit = FTR\,Revenue - FTR\,Cost \tag{6.37}$$

$$FTR\,Profit = \sum_{k \in \mathbb{K}_g} \Delta LMP_k - FTRP_k \tag{6.38}$$

where $\mathbb{K}_g$ is the set of FTRs that the generator g posses and ΔLMP_k is the difference between sink and source nodes of line k.

In the result tables, only the FTR directions with positive reward values are shown since the negative direction values are the negatives of exactly the same price value. Unless stated in the results, the firms do not bid for negative reward valued FTRs.

In the validation example, since there is no capacity limit, the LMP at each node is equal to that at the other nodes. Due to this fact, the cheaper generator, i.e., Generator 2, produces more than the expensive generator, i.e., Generator 1, as shown in Figure 6.10 where the green stem plots show the generation values for the infinitive case.

The transmission loads on the transmission lines are also as expected as listed in Table 6.4. Lines 2 and 3 bring a total of 100 MW into node 3, this being equal to the total demand at this node. Similarly, the total value of outflows from the generator nodes is equal to the total generation at these respective nodes. Since the LMP at each node is equal to that of the others, there is no reward value for any FTR in this scenario. As a result of the FTR market as seen in Table 6.4, the firms do not need to acquire any FTR.

B) Results for *Line 3 Capacity* = 50 MW

When line 3 is changed into a bottleneck line by altering its capacity to 50 MW the following result table is obtained:

Electricity Market Results							
LMP		Transmission Loads		Energy Allocations		Electricity Profit	
Node(n)	LMP(€)	Line(k)	t_k(MW)	Gen(g)	p_g(MW)	Gen(g)	R_g(€)
1	45.27	1	0	1	50	1	1250
2	27.16	2	50	2	50	2	750
3	63.38	3	50				
FTR Market Results							
FTR Prices			FTR Allocations			FTR Profit	
Line(k)	Reward(€)	Price(€)	Gen(f)	Line(k)	T_f^k	Gen(f)	Profit(€)
1	-18.11	-18.03	1	1	-12.50	1	6
2	18.11	18.03		2	12.50	2	6
3	35.72	36.06		3	25.00	Total Profit	
			2	1	-12.50	1	1256
				2	12.50	2	756
				3	25.00		

Table 6.5: Electricity-FTR market results for validation example with bottleneck line

Because of the congestion on line 3, transmission loads on the lines change to $[0,50,50]$ from $[-6,46,53]$ and resultantly the generation alterations to $[50,50]$ from $[41,59]$, as expected. The first generator gets the advantage of the congestion by selling more than the uncongested case and increases its profit to €1250 from €764, whereas the profit of the second generator drops from €1156 to €750. The cost of generation in the congested case is depicted in Figure 6.11.

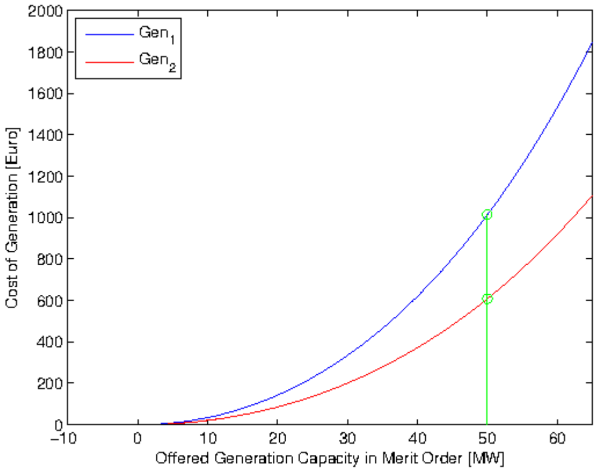


Figure 6.11: Cost of generation for validation example with bottleneck line

The FTR market values also change dramatically. Since the price differences between LMPs are equal to the reward values for the FTRs, positive values are listed for this column in Table 6.5 in contrast to Table 6.4. The firms are assumed to bid at the reward values of

FTRs with a slight decrease due to risk averseness, as explained in the previous section. Hence, the firms bid around the reward values with a very low risk-averseness factor γ. The minor total profit of about €6 and slightly lower values for FTR prices compared to the reward values are due to the risk averseness factor. The FTR allocations are also in proportion to the reward prices as expected. The simultaneous feasibility condition in equation (6.30) limits the number of FTRs to its current number.

One should realize that some players may directly benefit from the congestion inefficiency. Moreover, the total profit of the firms may increase, as is the case in this scenario. The total electricity profit of the firms increased from €1920 to €2000. Indeed, one strategic behavior of the firms could be to create congestion in order to benefit from it. This sort of behavior is well studied in the literature. Joskow and Tirole (2000) show in their study that generators can leverage FTR market power if it is in the importing region by curtailing generation to increase the value of FTRs. Similarly, Babayigit et al. (2010) show that generators have an incentive to purposely curtail generation to increase their own FTR reward value. Rourke et al. (2003) also simulate the electricity market and show that the market mechanism is prone to strategic behavior which is based on generation curtailment by the generators. It is possible to reproduce the results found in the literature by using the framework provided here.

Additionally various other strategic hypotheses can be tested using the Electricity-FTR workbench that is introduced above and validated with a simple model. One of these hypotheses regarding the strategic gaming behavior in the electricity markets is presented in the next section. In this scenario it is shown that the generators can use their private knowledge to game the FTR markets, which is understudied in the literature.

Scenario: Hidden knowledge game

In contrast to generation curtailment-based strategic behavior discussed in the literature, an example of strategic behavior based on capacity expansion knowledge that can be kept confidential by the generation company is discussed in this research. In this scenario, a firm increases its electricity capacity in the next iteration of the electricity market but does not inform the market about this move. So, in contrast to generation curtailment example in the literature, an example of strategic behavior based on generation increase with hidden knowledge is provided.

For simplicity the example is built on the bottleneck line scenario of the validation example that was discussed previously. Suppose the scenario is run for three years and at the end of each year the FTR market is run as depicted in Figure 6.12. The generators submit a valuation set for the FTRs, i.e., $\mathbb{B}$ as explained in Section 6.5.2 and depicted in Figure 6.4.

As shown in Figure 6.5, the firms forecast the following year's electricity market prices to assess FTR valuations. According to this, at the end of the first year, FTR distributions to each of the generators are $[-12.50, 12.50, 25]$ MW, as in validation example. For the second year exactly the same results as those shown in Table 6.5 are obtained.

Now suppose that, in the second FTR market at the end of the second year, Gen_1, which is the expensive generator, invests in a technology that improves its generation technology and decreases its electricity cost for the third year. However, Gen_2 is not aware of this upgrade. With the leverage of the upgrade, Gen_1 can offer a less expensive supply function, e.g., $(\alpha_1, \beta_1) = (150, 45)$ instead of $(150, 50)$ in the first two years of the scenario. This would mean a different LMP settlement for the third year and Gen_1 is the only player that can correctly forecast the LMPs of the third year. This hidden knowledge results in the following Electricity-FTR market result for the third year, which is correctly forecasted only by Gen_1;

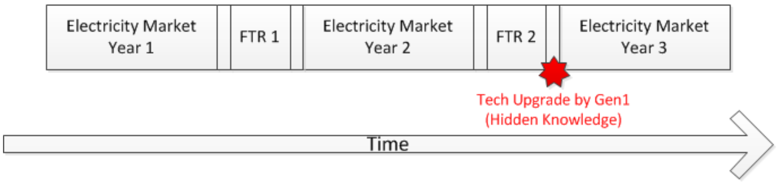


Figure 6.12: Hidden Knowledge Scenario flow

Electricity Market Results

LMP		Transmission Loads		Energy Allocations		Electricity Profit	
Node(n)	LMP(€)	Line(k)	t_k(MW)	Gen(g)	p_g(MW)	Gen(g)	R_g(€)
1	36.22	1	0	1	50	1	1250
2	27.16	2	50	2	50	2	750
3	45.27	3	50				

FTR Market Results

FTR Prices			FTR Allocations			FTR Profit	
Line(k)	Reward(€)	Price(€)	Gen(f)	Line(k)	T_f^k	Gen(f)	Profit(€)
1	-13.58	-17.96	1	1	0	1	0
2	13.58	17.96		2	0	2	-657
3	27.16	35.92		3	0	Total Profit	
			2	1	-25	1	1250
				2	25	2	93
				3	50		

Table 6.6: Electricity-FTR market results for hidden knowledge game scenario (third year)

The first observation is that the price (i.e., LMPs) of electricity drops for every node but node 2. This is as expected, since the cheap generator Gen_2 resides at this node and any additional load here is satisfied by Gen_2. Since this transaction is only bounded by the price of electricity that Gen_2 provides and the operational conditions of this generation does not change, the price at this node remains the same.

The decrease in LMPs causes a decrease in the 'Reward Prices' of FTRs. Hence, the real values of these FTRs drop. However, since the technology improvement by Gen_1 is a private knowledge, Gen_2's incorrect forecast for the third year causes overvaluation of the FTRs, which is depicted in the *FTR Price* column, as compared to *FTR Reward Prices* in Table 6.6.

Correctly forecasting the real value of the FTRs, Gen_1 bids low for the FTRs and eventually leave all the FTRs to its competitor, Gen_2. The financial result of the FTR overvaluation is the net deficit of €657 to Gen_2 in this scenario.

6.6 Conclusions and policy implications

The electricity demand is ever increasing, and so is generation in an effort to meet demand. Moreover, the volume of cross-national trade has increased in electricity sectors just like many other industries, with the advent of globalization. All these changes cause an increase in congestion problems on the electricity transmission lines. Since congestion is not a static phenomenon in terms of time and location but rather varies in these terms, and building excessive amounts of transmission lines is not economically viable, the electricity transmission industry has to manage and mitigate congestion.

Congestion typically increases the price of electricity sold to the end consumers by additional congestion costs. This congestion cost is not a physical cost but a rent created due to the congestion. "Who will collect this created rent?" is a question that the congestion management method has to tackle. Furthermore, incentives for long-term investment in the transmission lines would be affected by the particular congestion management mechanism to be deployed in an electricity market. Moreover, in the pursuit of designing a congestion management method, strategic behavior of the market participants is an imperative concern. The implemented congestion management method might provide various opportunities for strategic behavior, which is the focus of this thesis.

Considering the electricity supply industry and strategic behavior therein, in this chapter, first two major strategic management issues are presented – congestion management and market power mitigation. Sidelining market power mitigation, the chapter focused on two major families of policy remedies for the congestion problem of the electricity transmission grids – physical transmission rights and financial transmission rights. The problems regarding the abuse of market power were discussed and some conceptual methods for congestion management were presented. Physical transmission rights are designated as the classical method of congestion management, whereas financial transmission rights are mentioned as a relatively new policy instrument. Furthermore, the progress in Europe is discussed in relation to the aforementioned issues and solutions. The ambition of a pan-European grid is being actualized, although some issues are still to be addressed, such as the management of congestion and the transmission lines.

Along these lines, understanding and assessing the strategy-proneness of the congestion management techniques remain as a research gap. Modeling and simulation has long been an important contributor in understanding the challenges and tackling the aforementioned strategic issues, as discussed throughout the chapter. Despite the early promising results in the literature, which have usually sidelined the strategic aspect of the congestion management methods, more work is still needed to assess the various congestion management methods.

In order to assess the strategy-proneness of the FTR method, a coupled electricity-FTR market simulation is built in this research. The model is used to simulate a scenario of strategic behavior based on hidden information. The scenario clearly shows that hiding private information, which is about a generation technology upgrade in this case, can give a generation company or any other market participant a tremendous market edge, making FTR markets quite information-sensitive. The information-sensitiveness clearly serves the incumbent firms, which have a larger presence in the generation market and hence, more opportunity to hoard information. As a result, introducing FTRs without a mechanism to protect small players from information hoarding would conflict with the goal of creating a perfect market with a low barrier of entry and a high number of players.

As far as the policymaking is concerned, the main learning point of this study is that FTR markets can offer further opportunity for market participants in the electricity-FTR market. FTR could be an appropriate mechanism for generators to hedge their congestion risk. However, the increasing complexity of the total electricity system would render the system more prone to strategic behavior. In addition to the strategic behavior by creating congestion that is discussed in the literature, strategic behavior through hidden knowledge is shown in this study. On the other hand, the other congestion management methods have their respective disadvantages as well as advantages with respect to the FTR scheme analyzed in this study. A comparison of different schemes falls outside the scope of this study and can be treated as a future extension.

As for possible remedies against strategic behavior based on hidden knowledge, policymakers might consider looking at the rules and regulations of the stock markets, as some analogy between the stock markets and FTR markets can be drawn as far as the hidden knowledge is concerned. In most equity markets, insider trading is forbidden and the stock mobility of the executives of the companies is heavily regulated. Some similar regulations regarding the FTR movements of the generation companies can also be implemented in FTR markets.

Chapter 7

Technology Innovation in Liberalized Electricity Sectors

7.1 Introduction

In the previous two chapters, two game theoretic formal models regarding retail and wholesale electricity markets are analyzed. These models focus on two clearly defined examples of strategic behavior in liberalized electricity markets. In contrast to the previous two cases, in this chapter the scope is expanded and a more meta-level case in relation to strategic behavior in electricity sectors is examined. In this case the relationship between innovation and liberalization in electricity sectors is examined from a game theoretical point of view. After providing an exploratory view of innovation models in electricity and the energy sector in general, a specific notion of technology innovation in electricity generation is modeled.

The chapter is comprised of three sections. The introduction section provides an exploratory view of innovation in liberalized electricity sectors. In this section, firstly the nature and importance of technology innovation in liberalized electricity sectors is discussed in terms of the societal consequences of the lack of it. Then the lack of innovativeness in today's partly liberalized electricity sectors is demonstrated by using secondary sources for the US market. To make this point, a case that shows how low R&D spending is in comparison to other major sectors is provided. Secondly, the unique characteristics of the electricity sector with respect to technology innovation is discussed in this section. What possibly hinders innovation in electricity sectors is presented here. Finally, potential effects of decentralized decision making on the innovation processes in liberalized electricity sectors are discussed in Subsection 7.1.4. That subsection argues that the interplay of diverse interests of different stakeholders in innovation processes may determine the innovativeness of the sector. This view motivates the application of game theoretical models in exploring the conflicts of interests and alignments with incentive mechanisms.

The second section of the chapter reviews various game theoretical models of innovation in electricity sectors in the literature. Formal game theoretical models as an inquiry method is suggested in this section while giving a systemic review of the current models in the literature. It is argued that formal models of game theory can be used to better disentangle alternative hypotheses concerning industrial organization and innovation.

Finally, a signalling game of technology innovation mechanisms in the electricity generation industry is provided in Section 7.3. The focus is narrowed down to innovation in electricity generation technologies in the case provided in this section in order to apply game theoretical formal modeling. The model shows how the incentive mechanisms and the technical characteristics of the sector can cause a lock-in effect that can hinder innovation. A key message underlining the importance of incentive mechanisms for technology innovation is taken from the model.

Innovation is a broad term used loosely in various contexts. For this reason technology innovation is used as the focus of this chapter, since innovation in technology is particularly examined. However, technology innovation terms is quite broad as well. Various classifications of technology innovation can be made, such as radical innovation or incremental innovation. In this chapter the meaning of technology innovation is firstly used loosely to encapsulate various sorts of innovation but later narrowed to a particular sense in the game theoretical model in Section 7.3. In the introduction section, innovation refers to any sort of novelty, both incremental and radical, in electricity sectors. This is a high level discussion that aims to set a background for the game theoretical model that follows. In contrast to the introduction section, Section 7.2 aims to provide examples from the literature that study innovation in electricity and energy sectors. This section shows that the game theoretical model presented later in Section 7.3 belongs to and underlines the scientific gap in such models. Finally Section 7.3 provides a game theoretical model in which innovation has a narrow meaning. The type of technology innovation in this model points to any novel technology that can change the production function defined in this model. Technology innovation is an exogenous variable in this model, and its effects are discussed.

7.1.1 The nature of the problem and its consequences

Electricity sectors are lacking in innovation. This is despite the implicit assumptions by governments, regulators and non-governmental organizations that liberalization would encourage and improve competition and hence innovation (Jamasb and Pollitt, 2008, 2011). One criticism for the regulated electricity sector was that it was allegedly too heavy to innovate. The monopolistic structure of the electricity provider has not provided enough incentive to innovate. Thus, one of the main arguments in favor of the liberalization operation in the electricity sector was that it would enable competition and hence innovation.

In this section evidence for the current conduct of innovation is assembled in the sector using secondary sources and a review of the contemporary literature. It is concluded that an innovation gap is highly consequential for the electricity supply industry, consumers and the environment.

The electricity supply industry consists of four main segments. The first segment entails the generation of electricity, including the conversion of energy into usable form, and the production of electricity. The second segment involves the long-distance transshipment of electricity to customers, known as transmission. The third segment is the distribution network, which involves the supply of electricity at a local or regional level. The fourth and final segment of the electricity supply industry is the retail segment, which involves billing and the receipt of payment from customers.

The societal consequences of limited innovation in energy supply are potentially severe. Four consequences are explored: systemic, environmental, industrial and consumer.

The first consequence is systemic. The United States electricity sector, once described as Balkanized, has undergone a wave of mergers and consolidation, with a profound impact on the structure and organization of the grid. The European grid is undergoing a period of interconnection and market consolidation, corresponding to increasing levels of electricity trade across member states. This corresponds to calls to develop a more expansive high voltage grid, limiting congestion as well as losses incurred by long-distance electricity transport. The grid may well bind a number of conventional as well as sustainable sources of electricity generation, located wherever such sources are most cost-effective (De Decker and Woyte, 2013). Thus, energy grids are growing in scale and scope – a failure to innovate may mean a failure to upgrade and modernize the grid.

The second consequence is primarily environmental. There are potentially severe negative externalities for the environment, and also for sustainability, created by a lack of innovation in the electricity sector. Carbon dioxide is only one, fairly limited, measure of environmental impact for electricity generation. Nonetheless, even among fossil fuel-burning plants of the same power generating capacity, there are major differences in carbon output. There are differences of two to three orders of magnitude in CO_2 output stemming from fuel choice, and another one or two orders of magnitude which stem from the choice of combustion technology (Wheeler and Ummel, 2008). Fuel choice, as well as combustion technologies, are a source of innovation in the sector.

A third consequence is faced across dependent industrial sectors. Electricity is a general purpose service, which underlies many other productive activities in society. When electricity is compromised, so are many other sectors of the economy. A 2012 economic input-output analysis of Canada concluded that nearly 350 billion dollars of new electricity infrastructure will be needed in the next twenty years. This investment will provide substantial returns to the economy. Each dollar spent in infrastructure will return 0.85 cents in economic growth, and will provide a corresponding increase in growth, productivity and employment in other sectors. The construction industry, as well as heavy equipment and machinery sectors, are the most immediate private sector beneficiaries (Coad et al., 2010).

The fourth consequence is the consumer. Consumer willingness to pay in the developing world has been estimated at roughly $1 per kilowatt-hour (World Bank Independent Evaluation Group, 2008). Although world electricity costs vary widely, $0.16 per kilowatt-hour is a serviceable average cost. The difference between cost and willingness to pay is nearly an order of magnitude, indicating a very substantial consumer surplus attained through electricity usage. This value climbs still higher when the value of lost loads are considered. Consumers are willing to pay one or two orders of magnitude higher than market rates during times of outage (Kariuki and Allan, 1996). These values are only over the short duration, and the willingness to pay would undoubtedly declines over the long term as consumers substitute away from electricity. Nonetheless, such studies demonstrate considerable consumer value to be gained from reliable electricity services. Innovation gains directly contribute to lower electricity costs, higher reliability, and therefore a higher consumer surplus. Given these four consequences, society as a whole should be concerned with innovative outcomes in the electricity sector.

7.1.2 Evidence for limited innovation in the sector

Part of the evidence of limited innovation derives from innovation inputs. The US energy industry invests less in R&D than other sectors, even those industries which are directly comparable in terms of learning and scope Table 7.1. Consider for instance that while electrical equipment and appliance companies spend 2.7% of their revenue on R&D, energy extraction companies spend only 0.4%, and the energy industry as a whole spends only 0.3%. The utility sector is still lower in R&D intensity, at 0.1% (American Energy Innovation Council, 2010; Brown, 1980; Coad et al., 2010; De Decker and Woyte, 2013; Hausman and Neufeld, 2004; Wheeler and Ummel, 2008).

Sector	R&D Intensity
Computer and electronic products	10.1
Chemicals	6.1
Information	4.8
Professional, scientific and technical services	4.5
Machinery	3.5
Health care services	3.5
Electrical equipment, appliances and components	2.7
Transportation equipment	2.6
Printing and related support activities	1.9
Nonmetallic mineral products	1.9
Fabricated metal products	1.6
Furniture and related products	1.4
Retail trade	1.3
Real estate, rental and leasing	1.3
Paper manufacturing	1.2
Plastic and rubber products	1.1
Wholesale trade	0.8
Wood products	0.7
Beverage and tobacco products	0.6
Textiles, apparel and leather	0.6
Food	0.4
Primary metals	0.4
Mining, extraction and support activities	0.4
Finance and insurance	0.3
Energy	0.3
Utilities	0.1
Transportation and warehousing	0.1

Table 7.1: R&D funding by sector in 2012 (National Science Board, 2012)

There are strong correlative, and perhaps causative, studies linking research and development funding to innovative outputs, including patenting activity. While recognizing that learning by doing is a potentially significant source of innovation, Jamasb (2007) argues that learning by research is a much more significant factor shaping electricity generation. One should therefore be concerned regarding the state of development funding in the electricity supply industry. Evidence from the United States, the United Kingdom and Japan suggests that research and development spending has declined in response to deregulation of the sector. The leading explanation for this decline is that research is risky. While public R&D is a public good which is expected to underpin industrial activity, private R&D is done with an expectation of return on investment. In the United States, there is evidence that there has been substantial underinvestment in public research and development in the electricity sector (Jamasb and Pollitt, 2011). But it is difficult to make the same observation for private funding.

It is unclear why this spending should be so low. The energy industry may rely in part on component innovation from the electrical equipment or machine part sectors. However, the industry still faces the need for architectural innovation, which is best performed by the industry sector itself. Second, it is clear that consumers demand for high reliability and high performance equipment.

Technology suppliers, while nominally not a part of this industry, remain an important source of technological innovation. Innovation may occur in technological supply as well as across all four segments. Recent shifts in liberalization have diffused innovation both upstream (towards the supplier) as well as downstream (towards the customer), leaving a lack of innovation in the major generation and distribution hubs of the industry (Jamasb and Pollitt, 2011).

Commercialization has induced new entrants to the electricity sector. These new entrants spend less on research and development than incumbents, apparently because they can appropriate the benefits of research and development from others without sponsoring their own research. This appropriation effect is only one factor among a varied set of industrial organizational inputs leading towards systematic underinvestment under a liberalized market regime. While new entrants are reluctant innovators, so are established incumbents. Furthermore, there is an apparent reluctance among electricity incumbents to invest in potentially disruptive new technologies (Jamasb and Pollitt, 2008).

7.1.3 Characteristics of electricity sectors in relation to innovation

Electricity generation and transmission dwells upon an archaic infrastructure, the origins of which date back to the 19th century in the Western world. In general, it is possible to state that the incentives for innovation are weak in both generation and transmission segments. In this subsection the lack of innovation in the electricity system as a whole is related to its innovation-related characteristics. In order to do this, the technological and institutional characteristics of the electricity system are examined.

The characteristics of the electricity system that hinder innovation are divided into two main categories: supply side characteristics and demand side characteristics. Furthermore, the characteristics of the sector that affects its innovativeness are systematically categorized. In Table 7.2 the characteristics of electricity sectors, as categorized in supply side and demand side characteristics, can be seen.

Electricity supply has some important characteristics that hinder the mechanisms for innovation. Two main categories can be highlighted in this regard, as seen in Table 7.2: experiment avoidance and political complexity. Experiment avoidance refers to the characteristics of electricity systems that encumber experimentation in the system. As a metaphor-

Supply side characteristics	**Demand side characteristics**
Experiment Avoidance: -Economically critical -Capital intensiveness	Lack of demand response: -Insensitive to product diversity
Spatial Dispersion: -Political complexity -Natural monopoly	Lack of demand elasticity: -Insensitiveness to marginal price

Table 7.2: Characteristics of electricity sector that hinder innovation

ical example, the human body has a high experiment avoidance, as many, if not all, arbitrary experimentation on the human body could incur expensive costs. Looking back at the anecdotal examples of innovation, one may spot various innovations that have come about either by accident or trial and error, emphasizing the importance of experimentation for innovation.

The first characteristic that one can credit in this regard is the fact that electricity supply systems are economically critical systems that need to operate at a satisfactory level in any situation. The satisfaction level, as far as electricity systems are concerned, is very high, since multimillion industries that run world economies depend on electricity as their main source of power. Economic criticality of electricity brings about the intolerance to blackouts or brownouts. Thus, experimentation with the whole system as a fundamental means of innovation is not usually a viable option in electricity supply system.

Moreover, regarding another important ingredient of innovation, financial capital, the electricity supply system has harsh handicaps. The electricity supply system is inherently a capital-intensive system. The first major problem is the fact that this spatially dispersed and economically critical infrastructure needs immense sunk costs to renovate. Another problem associated with the costs is the question “Who would pay for it?”.

In addition to the experiment avoidance characteristic of electricity, its spatially dispersed nature complicates the incentives for innovation. The system spans over a large geographic area, involving several political and localized actors as well as different geographical conditions. This results in a need for extensive collaboration and some involvement of the political authority to make any change into the system. Also in relation to the economic criticality of the system, governments have to regulate the market to safeguard electricity supply, which results in the reduction of degree of freedom to experiment and innovate. Especially in politically fragmented Europe, coordination work is prone to be challenging and creation of overarching institutions can be cumbersome. This institutional layer of the electricity supply system constitutes a major constraint on innovation processes.

As for the demand side of electricity, two major characteristics affect the innovativeness of the electricity sector, as seen in Table 7.2.

“Innovations are done to attract more customers to the product or service.” This assertion presumes that customers are already attractable and are sensitive to the changes in the product. As far as electricity is concerned, it is generally considered a commodity and added value is usually ignored by the consumers. This notorious behavior of electricity consumers is observed especially in the reactions of consumers to increasing electricity prices.

Moreover, the experience of offering green energy to the consumer shows similar results.

Green energy has emerged as a quality of electricity, which is traditionally considered as a featureless commodity. Various studies (Bird et al., 2002; Jacobsson and Johnson, 2000; Torriti et al., 2010; Zarnikau, 2003) dwell on this issue and somehow mixed perspectives are demonstrated. While many of the studies claim that demand response has a high potential for energy efficiency concerns, the response to efficiency incentives and green energy is usually low. Bird et al. (2002) points out that most markets have a penetration rate of less than 1%. Furthermore, they call for more favorable market conditions and even government back-up in being able to provide green energy. Wiser (1998) goes one step further and shows how consumers behave as free-riders in the green energy discussion; he suggests various strategies for marketers to boost green energy marketing.

7.1.4 Formal models of innovation processes

In the preceding subsections, the importance of innovation in the electricity sector is stressed, some evidence for lack of investment in the sector is provided and some innovation-related characteristics of the sector that might hinder innovation processes are highlighted. In presenting the innovation-related characteristics, the aim is to gain insight into why innovation does not pick up in liberalized electricity sectors. From this point on the chapter will focus on the strategic behavior of the market participants, particularly on the self interests of the stakeholders and the incentive mechanisms of the market. After all, one of the major effects of liberalization is creating different actors, interests of which do not always overlap. To analyze the interplay of the interests of different actors, game theoretical formal models in the literature are examined in the next section, which will be followed by an original game theoretical model of technology innovation in electricity generation.

Several goals are aimed in particularly targeting formal models for further investigation. First, this is a useful complement to emerging empirical work. Although the game theoretical models are inappropriate for assessing empirical evidence and are unable to weigh the merits of alternative normative claims and debates, they are appropriate tools to assess interrelated interests of different actors and their strategies. Second, the assumptions about the workings of the market are under-examined. Formal modeling is an appropriate technique for adding rigor to the debate, although it has inherent limitations. The following section presents a review of game theoretical models of electricity innovation, which will be followed by an original game theoretical model of technology innovation in the electricity generation sector.

7.2 Game theoretical models of electricity innovation

In this section some formal models in the literature that utilize game theory in electricity innovation contexts are examined. A literature search for the key words energy, game theory, innovation and technology constitutes the base of the literature presented here. Comparatively few research articles on the matter were found. There are several reasons for this lack. There is a wide variety of political economy articles of strong relevance. However, few of these articles discuss the electricity sector in specific, despite compelling evidence that the industry has specific institutional and technological features which should be addressed.

	Nature of Innovation	Nature of Market Structure	Exogenous Factors	Conclusions
Tirole (1994a)	Technical process	Public-private partnership	Electoral factors	Public sector management of innovation is challenged by commitment factors.
Tirole (1994b)	Technical process	Public-private partnership	Multi-principal government	Multi-principal governments foster affordable innovation.
Tirole (1994c)	Product research	Public sector	Information witholding, information rent	Multi-agent contracting permits robust, societal-level gathering data in support of policymaking.
Schlecht (2003)	Product development	Market with limited entrants	Learning, discount	Negative discounting and expensive learning prevent market entry. Affordable learning encourages competitive entry.
Montgomery (2005)	Technology innovation	Tragedy of commons; climate change		Market-based environment policies of cap-trade and emission taxes cannot provide a sufficient incentive for technological change to mitigate climate change.
Bosetti (2006)	Technology innovation	Tragedy of commons; climate change	Welfare, GHG	Baseline scenario (business as usual) points to a stable energy-mix, minor R&D investments and a resulting catastrophe
Tavoni (2009)	Organizational process	Cooperative	Size of community, social norms	Radical innovation can be sustained but co-existence of market and cooperatives are likely.
Urpelainen (2011)	Product research	Public-private partnership	Government subsidy, treaty enforcement	Market conditions cause underinvestment and a lack of information sharing.

Table 7.3: A table of reviewed formal models of innovation

Further, the literature lacks an explicit distinction between game theoretic and other formal accounts. Therefore there is a large group of papers which are untapped because of the lack of a unifying methodological label. Game theory is, after all, a "bag of analytical tools" (Osborne, 1994) which have informed economics and policy across multiple levels of discourse.

Of those papers identified not all were utilized. Liu and Nagurney (2009) presented a comprehensive market clearing model studying fuel and electricity competition with regional effects. However, there is no explicit modeling of innovation. Schlecht (2003) produces a two-stage game of product innovation and learning. There are two actors – a market leader and a market follower. A third market entrant is permitted by the strategies of the first two. The joint outcomes involve creating a monopoly, Cournot oligopoly, or alliance structure. The resultant outcomes are valued according to market structure, cost of learning, time discounting and a Cournot market structure on price. Along the same lines, Gritsevskyi and Nakićenovi (2000) underline learning and uncertainty in the models.

Tavoni and Telesca (2010) present a simple model of cooperation and defection in coordinated energy usage, leading to the potential adoption of energy saving and distributed generation solutions. The basic model involves two actor types – consumers and prosumers – who interact through a dilemma to mediate energy needs. Prosumers lose the efficiency of market sources of energy, but gain the inherent flexibility of cooperative arrangements in energy consumption. They regard the resultant cooperation in the model to be evidence of bottom-up market coordination, permitting radical new forms of organizational innovation. Osés-Eraso and Viladrich-Grau (2007) also contributed on social norms and common property along these lines.

Urpelainen (2011) presents a tractable model of international sustainable energy collaboration. There are m governments, and n companies associated with each government. Strategies involve subsidy for technology investment and the actual technology investment. Technology innovation is risky. After innovation, denial of information is possible, but this can be monitored with error by government. The resultant analysis is accomplished under market conditions, as well as pareto-optimality conditions. A clear market failure is demonstrated. Extensive analysis of when cooperative arrangements are possible is given, which depends in large part on the innovative character of the firm and the symmetry of country values. Adverse selection is possible in this model – countries can seek to induce others to innovate, appropriating the developments without innovating themselves.

The paper bases its claims on a very extensive literature base. The literature cited is a mix of formal modeling and qualitative discussion. The authors discuss the role of new technologies in the development of society. Then they posit that technology innovation warrants international cooperation (Fischer and Newell, 2008; Hoel and De Zeeuw, 2010). They list the obstacles to international technology cooperation. They further elaborate on the need for private action and discuss the intensely competitive relationships between companies (Katz, 1986; Parkhe, 1993). They further describe the nature of the international free-rider problem (Ockwell et al., 2008). A gap in the literature is recognized, the need for a strategic account of international technology cooperation (Parkhe, 1993; Teece, 1986). Part of the game stems from the fact that the general international cooperation literature has not examined the role of private companies (Fearon, 1998; Putnam, 1988). Thus, the literature on international cooperation must be amended with empirical material and theoretical ideas from a large literature base on collaboration and rivalry in high-technology industries

(Tucker, 1991). Technological rivalry between companies, and between governments has been researched earlier (d'Aspremont and Jacquemin, 1988; Neary, 1994).

Tirole presents an implicit model of the costs and benefits of liberalization. The benefits of liberalization are that there is a greater diversity of products and services, and in providing this diversity, clear yardsticks can be obtained. Furthermore, having a new market principle with divergent interests may lead to more robust decision-making. However, liberalization will undoubtedly duplicate fixed costs and further, obscure the actual operating costs. These costs exert a counter-balancing force on the choice for a liberalized market (Tirole, 1994). There are three models from Tirole (1994) to be mention in this review.

Tirole's first model of liberalization involves the costs and benefits of commitment. The players are a firm and a government. If the firm faces high production costs, it will request the government to underwrite capital investment in subsequent periods. Knowing, however, that there is government turn over, the firm may not make the socially optimal investment. This generic model might apply, for instance, to new generation or transmission capability, although it is not described as such.

Tirole's second model involves a ministry which faces capital investment costs for societal infrastructure. The firm offers two stages of development – the first stage involves cost exploration, and the second stage involves actual implementation. The author argues that a single principled government would concede to implementation, even if cost overruns were high. In contrast, a government with multiple principles can hold costs down. This model is explicitly seen as one of process innovation leading to lower prices charged to consumers.

Tirole's third model involves information seeking for policy design. Tirole explicitly uses an energy innovation example, where the government is considering the respective merits of coal and nuclear powered plants. There are two agents who seek information on the government's behalf in favor of these policies. Tirole demonstrates convincingly that it is incentive incompatible for a single agent to present information on behalf of both policies. Further, it may be necessary to allow the agent to be a residual claimant in order to be fully and completely informed. More informed policy design, however, entails creating two agents. Further extensions involving sharing and withholding evidence, and positive and negative evidence, are sketched.

Bosetti et al. (2006) introduce a game theoretic model that is based on neoclassical optimal growth models. The model aims to analyze optimal climate mitigation strategies while taking transition of energy technologies into account. The world is divided into 12 macro regions, each of which is given the control of various investment decisions, i.e., investments in capital stocks, R&D, energy technologies and the consumption of fossil fuels. Each player behaves as a welfare maximizer, taking overall climate damages into account. Various interdependencies between the players are identified. Resultantly, the investment decisions depend on the game among the players with perfect sight. Both cooperative and non-cooperative scenarios can be made. Baseline scenario is formulated as a non-cooperative solution without any mitigation policy, which is benchmarked against mitigation involving scenarios.

Montgomery and Smith (2007) argue that the standard market-based incentive mechanisms such as cap-and-trade and tax on emissions cannot provide enough incentive to mitigate Greenhouse Gases (GHG) problems. Especially cap-and-trade policy has been recognized widely as concentrated almost solely on the market design and implementation of this policy in 1990s (Smith, 1991). Backstop technology, which is a hypothetical technology that can get GHG decline, is a model assumption that modelers frequently use. In the conventional thinking fostered in 1990s, backstop technology was expected to be invented in the distant future. However, modelers have never been concerned about how this hypothetical technology would be realized. The critical part of the analysis of Montgomery inquires how the backstop technology would be created. Hence R&D investment is highlighted as key to mitigating these problems as conventional market-based incentive mechanisms are claimed to not boost such mode of investments. In an exemplary game, which is called an R&D game, government and innovator behaviors are modeled, and it is shown that announcing future carbon limits or prices is not enough to attract private R&D investment.

One paper, which was not fully examined, is the work of van den Bergh (2007). Van den Bergh examines the policy aspects of environmental policy with respect to innovations in the energy domain. He supports, as a way to frame technological developments, the use of evolutionary economics concepts: diversity, innovation, selection, bounded rationality, path dependency and lock-in, and co-evolution. Evolutionary economics concepts largely draw from game theoretic foundations and are based on the concept of equilibrium (Smith et al., 1992). Dutch energy policies are assessed against this background. Various governmental reports and memoranda by various coordinating ministries are examined. Based on the analysis of mechanisms and objectives stated in these documents, an assessment with respect to evolutionary economics perspective is derived. Furthermore, van den Bergh (2007) uses his proposed framework to assess individual technologies at a lower level. Fuel cells, nuclear fusion and photovoltaic cells are assessed. The transition progress of each particular developing technology is examined from the perspective of evolutionary economics. At a high level, van den Bergh (2007) shows a valuable example of use of evolutionary concepts in energy policies.

The reviewed models are universally pessimistic about the potential for innovation in the electricity sector. The models examine a variety of different actors, incentives, and structures in the industry. The models find not one market failure but many in the industry. One cannot conclude from these models that the industry in the real-world is lacking in innovation. There is, however, compelling empirical evidence for this fact. Yet the models presented are potentially plausible representations of the state of incentives in the industry, and they do point to potential obstacles which may need to be removed before an innovative market is able to emerge.

More convincing still would be a positive model of how an electricity innovation process ought to function. The interplay of the interests of generators and machine vendors, who are the innovators of the new generation technologies, and the incentive structures remains to be written. Such an account ought to describe how profits and other incentives should be allocated to ensure the adoption and uptake of new technologies. Then a more balanced account of the successes and failures of the current innovation system might be considered in light of the actual current state of the industry. In the next section, a game theoretical model of technology innovation in the electricity generation sector is proposed as a step forward in this domain.

7.3 Generation technology innovation game

In this section an original game theoretical model of an innovation in the electricity generation sector is presented. The model features a simple supply chain of electricity as depicted in Figure 7.1. Generators provide electricity to retailers through an electricity wholesale (or spot) market and retailers supply electricity to the end consumers through a retail market.

Figure 7.1: Electricity supply chain

The electricity generation technology used by the generators to produce electricity is the concern of the game defined here. In this context ‘innovation’ is defined as a novelty in the generation technology. This innovation may translate into an improvement in product quality and/or a change in the quality of the product, i.e., electricity.

With the hypothetical innovation that is referred to in this game, potential disruptive technologies as well as incremental improvements are captured. A new generation technology, similar to wind power, or an incremental improvement of current generation technologies, can qualify for our hypothetical innovation in our model.

Any innovation one can think of in this context is bounded by capital. Thus capital investments play a central role in our model. It is assumed that the amount of capital investment by the producers is necessary for the technology innovation to occur.

Figure 7.2 shows the scope of the innovation game that is considered here. ‘Equipment vendors’ represent the hypothetical innovation player and are responsible for providing the necessary production machinery to the electricity supply industry. Beyond providing necessary production machinery and equipment, one may assume that the equipment vendors provide other types of logistics such as personnel, production methodology and technology to the generators or producers. This would mean that the innovation player may also be assumed to be universities and/or research institutions, which provide these qualities to the industry, instead of equipment vendors. However, equipment vendors are used for the sake of illustrative purposes.

In Figure 7.2, the boundaries of the game that is considered here is drawn with dashed lines. The game is concerned with the relationship between generators and equipment vendors as well as retailers. Two parts of the innovation game are considered here. The first part is a generator-equipment vendor game between equipment vendors and a single generator. It is assumed there are various generators similar to the one considered and that they sell electricity to the retailers in a wholesale market. Thus they bid their electricity capacities to the market with their marginal cost. The supply and demand balance of the electricity determines the market price of electricity. The market price and quantity of electricity bought by the retailers determines the payoffs to the generators. The market mechanisms and the generator and equipment vendor payoffs are elaborated on in the following subsections. This part of the game shows that the innovation player, which is the equipment vendor in this game, has more of a follower role and a generator’s market power determines whether the sector enters into innovation mode or not. Furthermore, it shows that the cost of electricity

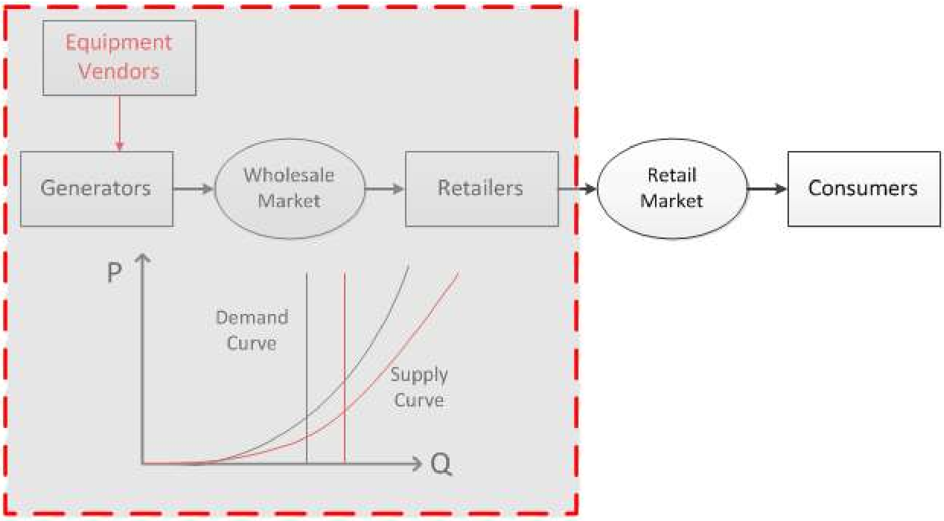


Figure 7.2: Scope of the game

and the demand response to quality is at least as important as the cost of innovation. This part of the game assumes that the demand of electricity does not shift from one generator to the other despite the cost of generation decreases for that particular generator, which is a limiting assumption. To cover this ill-natured assumption, Part II of the game is presented, which is a duopoly generator game.

The 'duopoly generator game' extends from the generator-equipment game by considering a duopoly wholesale market. The generators invest in their respective generation technology innovations. The innovations potentially change the cost of electricity that these generators provide. Since they share the same customer base, the demand can shift depending on the cost of the electricity that each of the generators provide. The details of this game can be found in Subsection 7.3.6.

7.3.1 Part I: Generator - equipment vendor game

In Figure 7.3, the game in extensive form is depicted. In this conceptualization, one generator and an associated equipment vendor, which is the innovation player in this conceptualization, are assumed. The innovation player symbolizes an actor that increases the chance of innovation. It can be thought of as an external company or an internal business unit attached to the generator. The equipment vendor decides whether to *innovate (I)* or continue its operations without innovating, i.e., with *status quo (S)*. The equipment vendor (EV) makes its decision according to its estimation of the resolution of the game. The generator (Gen), on the other hand, has the option to *invest (V)* in a generation technology innovation or *not invest (N)*. The decisions are made simultaneously, the generator is not sure about the decision of the equipment vendor. Thus, in our model, a probability estimation, γ, for the generators regarding the decision of the equipment vendor, is assumed. In reality this probability estimation by the generators can even be one or zero, i.e., the generator might be sure about the decision of the equipment vendor, depending on the circumstances. However, the most general form is assumed in this model.

Eventually four possible outcomes are depicted in the game tree. Each of the outcomes bring a corresponding payoff to the players. In the figure, these payoffs are denoted by G_n and EV_n for the n^{th} outcome for generator and equipment vendor respectively. In the following sections how we calculate these outcomes is discussed.

7.3.2 General equilibrium model of the wholesale competition

The economic relationship between the retailers and the generators determines the payoffs for the players. A perfect market between these players in the form of a classical general equilibrium model is assumed. It is assumed here that there is no shift in demand in this part of the game and will change this assumption in the second part.

A supply-demand curve as shown in Figure 7.4 determines the outcome of the market. Here a quadratic supply curve and an inelastic demand curve are assumed. The motivations for these choices are discussed in Chapter 5 and in the previous sections of the current chapter. Briefly speaking, merit ordering of the electricity capacity and the insensitivity of the consumer to electricity price changes are the respective reasons for these choices.

The quadratic supply and demand curves can be written as follows:

$$P = KQ^2 \tag{7.1}$$

$$Q = D \tag{7.2}$$

Two parameters characterize the market in this model. Quadratic supply parameter K characterizes the supply curve, whereas the demand parameter D characterizes the inelastic demand function.

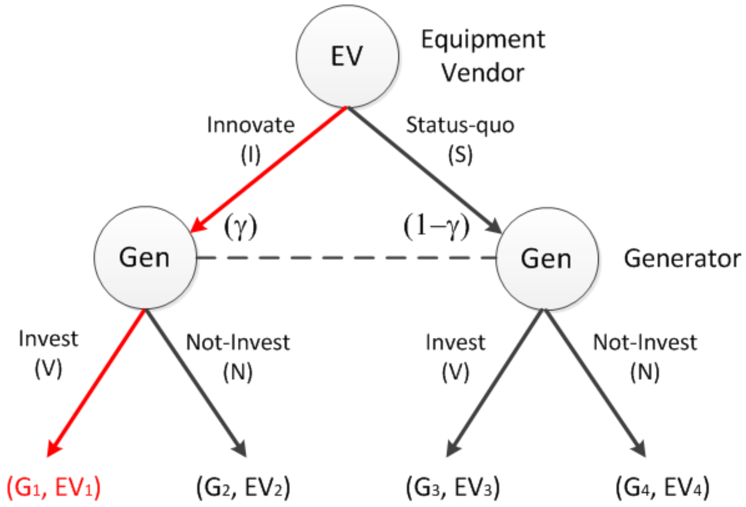


Figure 7.3: Extensive form

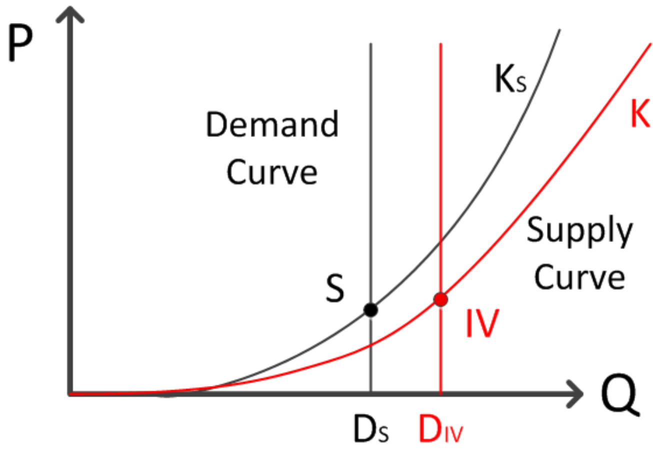


Figure 7.4: Supply-Demand Curve

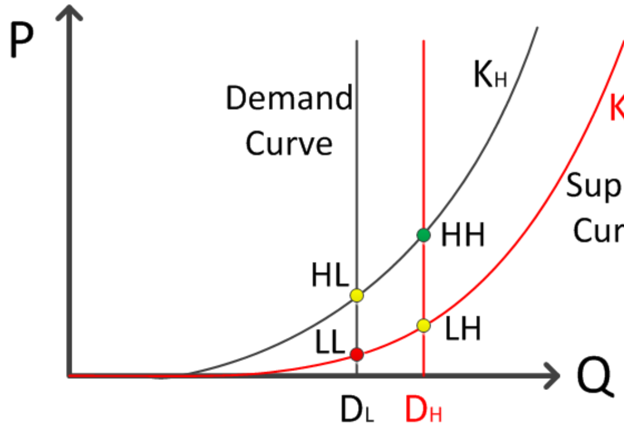


Figure 7.5: Supply-Demand Curve

In Figure 7.4, the supply and demand curves are depicted. The first one, which is labeled with *S*, represents a status quo outcome of the game, whereas the second one, labeled with *IV*, represents *Invested Innovation* outcome. These two outcomes relate back to the game in extensive form in Figure 7.3. Only the first branch, which is the result of a combined Innovate (I) and Invest (V) actions, represents the successful innovation. The other branches miss the combined effort, hence the successful innovation in the model. Hence the parameter values, (K_{IN}, D_{IN}), (K_{SV}, D_{SV}), (K_{SN}, D_{SN}), which result respectively from *IN*, *SV* and *SN* actions of the players, are all assumed to be equal and are denoted as (K_S, D_S). The intersection of supply and demand curves marks the equilibrium point. The curves, hence the locations of these points, in the figure are arbitrary.

The order relations, hence the locations, of the equilibrium points are conditional upon the *K* and *D* values. It is not straightforward to call $K_{IV} < K_S$ (similarly, $D_S < D_{IV}$) or vice versa for every case. If one considers nuclear power as an example innovation, $K_{IV} < K_S$

holds due to the lower operating costs of nuclear power compared to the conventional fuels. However, *R&D* costs and the sunk costs may drive K_{IV} high during the first years of the innovative technology (nuclear power in this example) and later, the operating price of the technology may drop. Hence one should be beware of possible dynamic K_{IV} parameter. Similarly, if one considers a hypothetical power source that has a high initial cost but also attracts high demand from the consumer due to, for example, environment friendly characteristics of the technology, the innovation may be economically feasible.

In Figure 7.5 one may examine four possible outcomes of the retail competition. Depending on whether the supply parameter is high or low (K_H or K_L) and whether the demand parameter is high or low (D_H or D_L), these different outcomes may result. The nuclear power example, which accounts for a low supply parameter and low demand parameter, may correspond to the *Low-Low (LL)* equilibrium point in the figure, whereas a hypothetical power source that increases production costs while attracting more demand, may correspond to the *High-High (HH)* equilibrium point. If one compares the Figures 7.4 and 7.5, it is important to note the order relation of LH and HL points. Depending on the supply (K) and demand (D) parameters, either may result in a higher price or revenue, i.e., the multiplication of price and quantity.

7.3.3 Generator (Gen) and equipment vendor (EV) payoffs

The payoffs to the EV and Gen are determined based on the equilibrium point of the general equilibrium model discussed above. The Gen payoff can be written as follows:

$$Payoff(Gen) = Energy\ Revenue - Energy\ Cost - Investment\ Cost \tag{7.3}$$

$$Payoff(Gen) = P^*Q^* - \int_0^{Q^*} PdQ - \theta \tag{7.4}$$

where P^* and Q^* are the equilibrium points and θ is the investment cost associated with the *investment* action by the generator as illustrated in Figure 7.3.

Using equations (7.1), (7.2) and (7.4), one can derive the following result;

$$Payoff(Gen) = \frac{2}{3}KD^3 - \theta \tag{7.5}$$

where D is the inelastic demand parameter and K is the supply parameter.

The payoff for the equipment vendor depends on the *innovation cost* (θ) and the *implementation cost* (λ) of the innovation. The innovation cost is paid by the generator to the equipment vendor, but the implementation cost is paid by the equipment vendor for the costs to realize the innovation project. Typically the former metric is greater than the latter, due to the added value of the implementation of the innovation. When the generator decides to invest into the research for new innovation and the equipment vendor innovates (i.e., *IV* branch), payoff for the equipment vendor becomes positive. When the equipment vendor attempts to innovate but the generator does not invest into the technology (i.e., *IN* branch), the equipment vendor payoff is a net loss. When the equipment vendor does not opt for innovation, the result is null payoff for EV. Thus the equipment vendor's payoff is written as follows:

$$Payoff(EV) = Innovation\ Cost - Implementation\ Cost$$

$$Payoff(EV) = \begin{cases} \theta - \lambda & if \quad \text{IV} \\ -\lambda & if \quad \text{IN} \\ 0 & if \quad \text{SV or SN} \end{cases} \tag{7.6}$$

Based on the payoffs determined above in equations (7.5) and (7.6), the branch payoffs $G_n, EV_n \quad \forall n \in \{1,2,3,4\}$ that are depicted in Figure 7.3, the following values are found;

$$G_1 = \frac{2}{3} K_{IV} {D_{IV}}^3 - \theta \qquad EV_1 \ = \theta - \lambda \tag{7.7}$$

$$G_2 = \frac{2}{3} K_{IN} {D_{IN}}^3 \qquad EV_2 \ = -\lambda \tag{7.8}$$

$$G_3 = \frac{2}{3} K_{SV} {D_{SV}}^3 - \theta \qquad EV_3 \ = 0 \tag{7.9}$$

$$G_4 = \frac{2}{3} K_{SN} {D_{SN}}^3 \qquad EV_4 \ = 0 \tag{7.10}$$

Assuming $K_S = K_{SV} = K_{SN} = K_{IN}$ and $D_S = D_{SV} = D_{SN} = D_{IN}$ the payoffs are simplified to;

$$G_1 = \frac{2}{3} K_{IV} {D_{IV}}^3 - \theta \qquad EV_1 \ = \theta - \lambda \tag{7.11}$$

$$G_2 = \frac{2}{3} K_S {D_S}^3 \qquad EV_2 \ = -\lambda \tag{7.12}$$

$$G_3 = \frac{2}{3} K_S {D_S}^3 - \theta \qquad EV_3 \ = 0 \tag{7.13}$$

$$G_4 = \frac{2}{3} K_S {D_S}^3 \qquad EV_4 \ = 0 \tag{7.14}$$

7.3.4 Game in strategic form

The game in strategic form is formulated based on the decision tree depicted in Figure 7.3, and the payoffs of the equipment vendor and the generator are derived above. As mentioned earlier, in our game the equipment vendor's decision is not transparent to the generator. The generator estimates a likelihood (i.e., α for strategy I) for the decision of the equipment vendor.

Note that in game theory context 'strategy' refers to one of the options a player can choose in a setting where the outcome depends not only on his or her own actions but on the action of the others. It is different than a 'move', which is an action taken by a player at any point in a game. On the other hand, a strategy is a complete algorithm that determines what the player would do for every possible situation throughout the game.

In our game, a generator's strategies are dependant on the choice of the EV. For example VN strategy of generator means "choose V (Invest) when EV chooses I (Innovate) and choose N (Not-Invest) when EV chooses S (Status quo)". Accordingly, the game in strategic form is populated as in Table 7.4.

		Generator			
		VV	VN	NV	NN
EV	I	$\theta-\lambda^{\star}$, $G_1\gamma+G_3(1-\gamma)$	$\theta-\lambda^{\star}$, $G_1\gamma+G_4(1-\gamma)^{\dagger}$	$-\lambda$, $G_2\gamma+G_3(1-\gamma)$	$-\lambda$, $G_2\gamma+G_4(1-\gamma)^{\dagger}$
	S	0, $G_1\gamma+G_3(1-\gamma)$	0, $G_1\gamma+G_4(1-\gamma)^{\dagger}$	$0^{\star}$, $G_2\gamma+G_3(1-\gamma)$	$0^{\star}$, $G_2\gamma+G_4(1-\gamma)^{\dagger}$

Table 7.4: Game in strategic form

In the table, the first (upper) payoffs are for the equipment vendor and the second (lower) payoffs are for the generator. The dominating strategies for equipment vendor are marked with a star sign ($\star$), and the dominating strategies for the generator are marked with a dagger sign ($\dagger$). The domination of the generator strategies occurs due to the fact that G_3 is strictly less than G_4.

Two strategies of the generator are strictly dominated by the other strategies, namely VV and NV. The common point of these two strategies is the second choice, that is "to invest when vendor plays S (Status quo)". Indeed, it is very sensible for the generator to refuse to invest when there is no effort from the vendor side, as this would mean a net loss for the generator due to the investment cost. Removing the dominated strategies, the game in strategic form is reduced to a two-by-two matrix game, as in Table 7.5.

		Generator	
		VN	NN
EV	I	$\theta-\lambda$, $G_1\gamma+G_4(1-\gamma)$	$-\lambda$, $G_2\gamma+G_4(1-\gamma)$
	S	0, $G_1\gamma+G_4(1-\gamma)$	0, $G_2\gamma+G_4(1-\gamma)$

Table 7.5: Game in strategic form (reduced)

There are two prevailing strategies of the generator, namely VN and NN as seen in the table. The first strategy (VN) reads "invest into the innovation when equipment vendor innovates and do not invest when equipment vendor does not innovate", whereas the second one (NN) reads "do not invest in any case". In the next subsection the solution of this game is discussed.

7.3.5 Solution of the generator-equipment vendor game

The choice of the equipment vendor is straightforward in this game. The equipment vendor opts for I when the generator goes for VN and prefers S when generator chooses NN. So the solution of the game boils down to the choice of the generator.

The decision of the generator is bounded by the relationship between G_1 and G_2. These two values are the results of two leaves of the game, depicted in Figure 7.3 and calculated in equations (7.11) and (A.10), respectively. When $G_1 > G_2$ holds, (I,VN) is the Nash equilibrium of the game whereas when $G_1 < G_2$ holds (S,NN) is the Nash equilibrium.

$$G_1 = \frac{2}{3} K_{IV} {D_{IV}}^3 - \theta \tag{7.15}$$

$$G_2 = \frac{2}{3} K_S {D_S}^3 \tag{7.16}$$

Hence for the condition $G_1 > G_2$ to hold, the following relationship between supply and demand parameters must be satisfied:

$$K_{IV} {D_{IV}}^3 - \frac{3}{2}\theta > K_S {D_S}^3. \tag{7.17}$$

If the inequality condition in equation 7.17 holds, the generator will opt for VN strategy and the equipment vendor will opt for I (innovate) strategy, which would mean that the companies engage in innovation. This is the desirable solution for the societal perspective.

If one examines inequality 7.17, there are three parameters that determine whether the inequality holds. These are technology related characteristics K (K_{IV} and K_S), demand-related characteristic (D_{IV} and D_S) and the innovation cost (θ). Importance of the demand-related characteristics was discussed in Subsection 7.1.3. The demand sensitivity for different types of generation technologies was highlighted as an important characteristic from the innovation perspective. Positive reaction of demand for a ‘better’ generation technology, such as an increase in demand for green electricity, is an important motivator for innovation. This fact manifests itself in our analysis, too. An increase in demand for a “better” technology would make the inequality 7.17 hold in our model. The last parameter, θ, denotes innovation cost paid by the generator to the equipment vendor. Clearly, as innovation cost increases it becomes more difficult for companies to engage in the desirable innovation mode.

Another observation that can be made is that even if some amount of demand compensation is granted, the capital intensiveness of the sector as discussed in Section 7.1.3 pulls down the incentives to invest for the generators. Decreasing this cost with financial incentives, such as R&D tax credits or subsidies, could make it easier for the companies to engage in innovation. However, it is important to note that even if the costs are handled to some extent, the potentially decreasing price of electricity with new generation technologies has to be compensated by demand increase, or the new generation technologies should not cause a drop in prices.

The parameter K is related to the supply cost curve of the total electricity in the market as formulated in 7.1 and depicted in Figure 7.4. According to the supply curve, a higher value for K would mean a higher cost of electricity. With a new technology, one might expect K value to drop, since people tend to think that the cost of electricity should drop with a new technology. However, our analysis shows that the decreasing electricity cost, which would eventually drives the selling price down, is economically a loss for the generators and hence repels generators from engaging in investment unless the new technology triggers an increase in demand, as observed in the equation 7.17. On the other hand, as discussed in Subsection 7.1.3, the electricity demand side is notorious for its insensitivity to the quality of the electricity. So one conclusion one can derive from this model is that the reason for low investment in electricity sector is caused mainly by this insensitivity of the consumer to a higher ‘quality’ of the electricity, such as ‘greener’ electricity.

If one assumes that demand is irresponsive to the quality of the energy (i.e., $D_{IV} = D_S$) and the cost of innovation is subsidized by a governmental regulation (i.e., $\theta = 0$), the following inequality results:

$$K_{IV} > K_S \tag{7.18}$$

which is required to be held for the companies to engage in innovation mode. This means that the cost of the electricity has to increase for generators to benefit from the innovation, in the case that the demand is irresponsive. However, the increase in the price of electricity is not the purpose of the innovation, nor does it provide an ideal situation from the global welfare point of view.

Note that in this part it is assumed that there is no mobility of demand between competing generators. Regarding the inverse relationship between the decreasing costs of electricity and the incentives to engage in innovation mode for the generators, one should consider the effect of competition too. A decrease in cost of electricity gives a generator an edge to capture some market share from the other generators. Would the captured market share break even, given the excessive costs of innovation for a investing generator? This issue is addressed in the second part of our game theoretical model, in which a duopoly generation market is modeled.

7.3.6 Part II: Generator duopoly game

The second part of our model attempts to deal with a missing factor, that is, the effect of the lower cost of production into the market share of the generators. Hence the second part involves a duopoly market in which two generators compete for demand in the same wholesale market as set in Part I of our model. The generators compete not only for generation demand but also consider the innovation investment decisions, just as in the first part. A drop in the cost curve of the electricity production (K) for a particular generator would shift the demand for the advantage of that particular generator.

Part I showed that the equipment vendor is a follower in game theoretical terms, i.e., a player whose decision is determined by the decision of another player. The decision of the generator is shown to determine the move of the equipment vendor and hence the outcome of the game. Furthermore, three factors were shown to matter in determining the solution of the game: the effect of the innovation to the supply cost curve of the electricity production (K), demand response to the quality of the electricity that is provided by the novel generation technology (D) and the innovation cost (θ).

In this part it is assumed that each generator has its own innovation partner, i.e., an equipment vendor. Since the equipment vendor was found to be a follower in the previous part, the decision of the generators are the focus in this part. When a particular generator chooses innovation option, it is assumed that the corresponding generator - equipment vendor pair *engage (E)* in innovation mode, otherwise the generator-equipment vendor *rejects (R)* engaging in innovation mode.

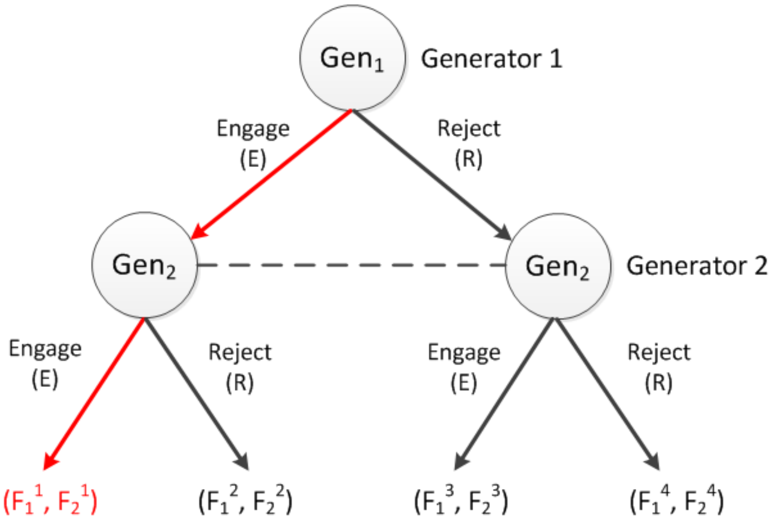


Figure 7.6: Duopoly generation game in extensive form

Figure 7.6 shows the decision tree of the duopoly generation game. The order of the game is specified, as Generator 2 follows the decision of Generator 1. However, since it is assumed that the generators move simultaneously and the game is an imperfect information game, the order of play does not matter. Generator 2 is assumed not to know the decision of the Generator 1 in advance in any case. The dashed lines show that the game is imperfect information, with two different information sets available to Generator 2.

Without any loss of generality, the game can be expressed in strategic form as in Table 7.6. Since the players play simultaneously, it is proper to represent the game as a two-by-two matrix game in strategic form.

		Generator 2	
		Engage (E)	Reject (R)
Generator 1	Engage (E)	(F_1^1, F_2^1)	(F_1^2, F_2^2)
	Reject (R)	(F_1^3, F_2^3)	(F_1^4, F_2^4)

Table 7.6: Duopoly generator game in strategic form

7.3.7 Generator payoffs

The payoffs of the generators depend on the revenue, energy cost and the investment costs, just as in the previous part. In this part of the game, however, total demand can swing from one generator to the other though.

$$Payoff(Gen) = Energy\ Revenue - Energy\ Cost - Investment\ Cost \tag{7.19}$$

$$Payoff(Gen_n) = P^* Q_n^* - \int_0^{Q_n^*} P_n dQ_n - \theta_n \tag{7.20}$$

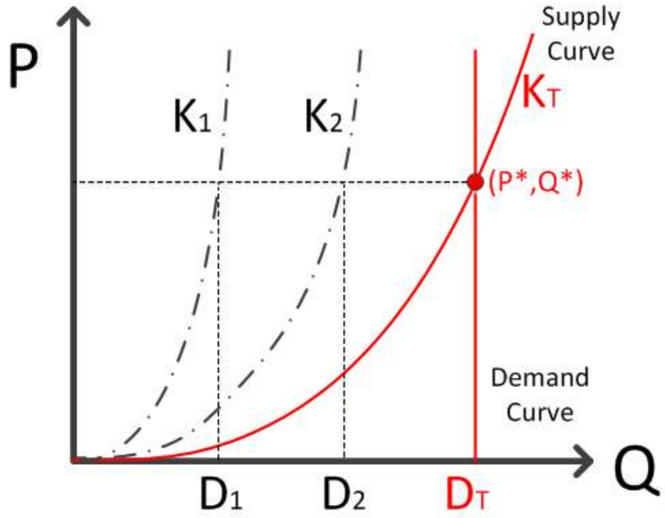


Figure 7.7: Supply-demand curve of the duopoly generation market

where (P^*, Q^*) is the equilibrium point of the supply-demand curve, Q_n^* is the corresponding amount of demand that generator n satisfies, P_n is the price curve of generator n and θ_n is the investment cost for that generator.

To better illustrate the payoffs, consider the supply-demand curve in Figure 7.8.

K_1 and K_2 technology parameters determine the supply-demand curves of the generator 1 and 2, respectively, with the following formula:

$$P_1 = K_1 Q_1^2 \tag{7.21}$$

$$P_2 = K_2 Q_2^2 \tag{7.22}$$

The sum of demands (Q) of each generator at a particular value of price (P) gives the combined supply-demand curve. At the equilibrium the following equations hold:

$$P^* = P_1^* = P_2^* \tag{7.23}$$

$$Q^* = Q_1^* + Q_2^* \tag{7.24}$$

Thus, at equilibrium, the total demand D_T is distributed among the generators according to their cost curves. The generator with the higher cost of electricity (K_1) ends up with a lower portion (D_1) of total demand (D_T), whereas the generator with cheaper electricity cost takes the lion's share (D_2).

The demand shares can be written with a proportion factor α as follows:

$$D_1 = \alpha\, D_T \tag{7.25}$$

$$D_2 = (1 - \alpha)\, D_T \tag{7.26}$$

Using equations (7.21), (7.22) and (7.23), one can find α as follows:

$$P_1^* = P_2^* \tag{7.27}$$

$$K_1 D_1^2 = K_2 D_2^2 \tag{7.28}$$

$$K_1 \alpha^2 = K_2 (1-\alpha)^2 \tag{7.29}$$

$$\alpha = \frac{1}{1+\sqrt{\frac{K_1}{K_2}}}. \tag{7.30}$$

The equation (7.30) shows that the proportion of demand, i.e., α, that a generator captures is inversely proportional to its cost curve parameter K. When the generators have the same cost curve parameter K, they both capture an equal share of total demand, as expected.

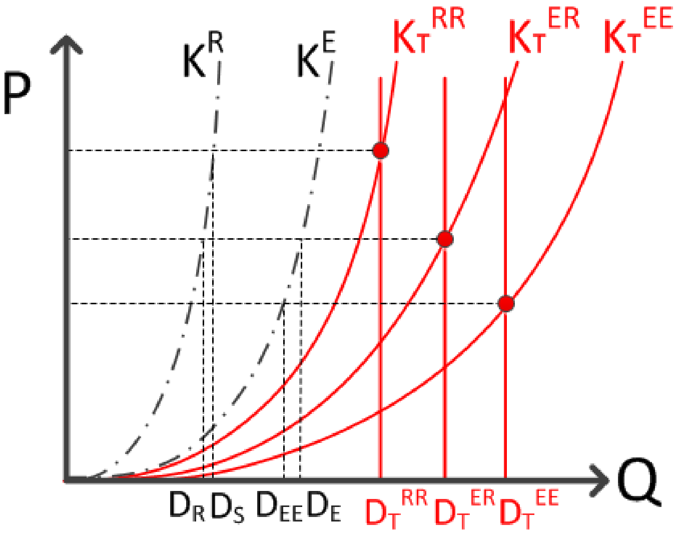


Figure 7.8: Different equilibria for different outcomes

The payoffs that are need to be specified in Table 7.6 are determined by the cost curve values, i.e., Ks, and total demand, i.e., D_Ts, for each situation depending on the decision of the generators to engage in or reject innovation mode.

In order to make the analysis easier symmetric parameters are assumed for the generators. It is assumed that each has an equal demand share at status quo (D_S), i.e., when both generators *reject*. When they both go for *engage*, they both receive an equal share (D_{EE}) due to the symmetry. On the other hand, when one of them engages and the other rejects, the engaging generator gets a higher demand (D_E) than the rejecting generator (D_R). In these three modes of innovation the total demand is written as $D_T{}^{RR}$, D_T^{EE} and D_T^{ER}, respectively.

Similarly symmetry is assumed for the cost curve parameters Ks. When one of the generators *rejects*, it ends up with a higher cost curve driven by a high K^R value. If it *engages* in innovation mode, it ends up with a lower cost curve driven by the parameter K^E.

Figure 7.8 shows three modes of innovation. As mentioned earlier, the summation of supply values of the generators at each price value gives the total supply curve at that mode.

The K values and D values are chosen for a scenario in which innovation decreases the costs and increases the demand. For the modes when both engage or reject, the total demand values (D_T^{EE} and D_T^{RR}, respectively) are divided equally between the generators. When one of them engages and the other rejects, the total demand D_T^{ER} is divided proportionally depending on the engagement and rejection cost curve parameters K_E and K_R as in equation (7.30).

Using equations (7.20), (7.21) and (7.22), the payoff for a particular generator at an equilibrium point can be written as:

$$Payoff(Gen_n) = \frac{2}{3} K_n (Q_n^*)^3 - \theta_n. \tag{7.31}$$

where K_n is the cost curve parameter and Q_n^* is the demand satisfied by the generator, which are determined by the mode of innovation. θ_n is the innovation cost, which is a null value if the generator rejects engaging in an innovation.

Accordingly, based on our assumptions and defined parameters so far, the generator payoffs, which are shown in the game tree in Figure 7.6 and in Table 7.6 in strategic form, can be written as follows:

$$F_1^1 = F_2^1 = \frac{2}{3} K^E D_{EE}^3 - \theta \tag{7.32}$$

$$F_1^2 = F_2^3 = \frac{2}{3} K^E D_E^3 - \theta \tag{7.33}$$

$$F_2^2 = F_1^3 = \frac{2}{3} K^R D_R^3 \tag{7.34}$$

$$F_1^4 = F_2^4 = \frac{2}{3} K^R D_S^3. \tag{7.35}$$

Resultantly, the game in strategic form can be written in closed form as follows:

		Generator 2	
		Engage (E)	Reject (R)
Generator 1	Engage (E)	$\frac{2}{3}K^E D_{EE}^3 - \theta, \quad \frac{2}{3}K^E D_{EE}^3 - \theta$	$\frac{2}{3}K^E D_E^3 - \theta, \quad \frac{2}{3}K^R D_R^3$
	Reject (R)	$\frac{2}{3}K^R D_R^3, \quad \frac{2}{3}K^E D_E^3 - \theta$	$\frac{2}{3}K^R D_S^3, \quad \frac{2}{3}K^R D_S^3$

Table 7.7: Duopoly generator game in strategic form

where

$$D_{EE} = \frac{D_T^{EE}}{2} \tag{7.36}$$

$$D_S = \frac{D_T^{RR}}{2} \tag{7.37}$$

$$D_E = \alpha\, D_T^{ER} \tag{7.38}$$

$$D_R = (1-\alpha) D_T^{ER} \tag{7.39}$$

$$\alpha = \frac{1}{1 + \sqrt{\frac{K_E}{K_R}}}. \tag{7.40}$$

As expected, the game is symmetrical, with multiple possible equilibria depending on the demand response to the innovation (i.e, D_T^{EE}, D_T^{RR}, D_T^{ER}) and the effect of the innovation on cost curve parameters (i.e, K^E, K^R) as well as the innovation. The solution of the game is discussed in the next subsection.

7.3.8 Solution of the generator duopoly game

In the first part of our model, it is pointed out that the solution of the game depends on the demand response (D) to the innovation and the effect of the innovation to the production cost curve (K) of the single generator that was modeled. In contrast to Part I, this part of the model takes competition between the generators into account, thus providing a leeway for a more general discussion regarding the level of innovation engagement of the generation companies in the electricity generation sector. However, the result still depends on the same factors.

The assumption regarding demand mobility might affect our result. It was stated that if the demand response is weak, a lower cost curve K would result in a drop in the price of electricity, which would not favor the generator. Thus it was concluded that the generator has no incentive to invest in innovation even if the innovation cost is fully subsidized in cases when the demand response is weak. One particular counter argument to our conclusion was that the increasing demand would increase the investing generator's demand and could prove to be beneficial for it. The second part is designed to answer the question of whether demand mobility is taken into account, a generator would invest in innovation.

If one considers the game in strategic form in Table 7.7, to be able to end up at an *Engage-Engage* state, which is the most innovative state, the following two inequalities have to hold:

$$\frac{2}{3}K^E D_{EE}^3 - \theta > \frac{2}{3}K^R D_R^3 \tag{7.41}$$

$$\frac{2}{3}K^E D_E^3 - \theta > \frac{2}{3}K^R D_S^3. \tag{7.42}$$

If one compares the equations 7.41 and 7.42 to the result of Part I in equation 7.17, one can see some similarities. First of all, the innovation cost, θ pushes the generators to not invest in innovation. Furthermore, a decreasing cost of electricity (i.e., $K^E < K^R$) is also unfavorable for innovation mode just as in the first part. And just as in the first part, increasing demand (i.e, $D^{EE} > D_R$ and $D^E > D_S$) would mean that it would be favorable for the generators to engage in innovation mode.

Also a similar result is obtained if the effect of K values to the innovation mode is analyzed. If one assumes a situation in which the innovation cost is fully subsidized (i.e., $\theta = 0$) and the demand is irresponsive to the innovation (i.e., $D_T^{EE} = D_T^{ER} = D_T^S$), the following inequalities must hold for the innovation mode:

$$K^E D_{EE}^3 > K^R D_R^3 \tag{7.43}$$

$$K^E D_E^3 > K^R D_S^3.. \tag{7.44}$$

Applying equations (7.36), (7.37), (7.38), (7.39) and (7.40) to inequalities (7.43) and

(7.44), these inequalities can further be simplified to:

$$\frac{K^E}{8} > K^R(1-\alpha)^3 \tag{7.45}$$

$$K^E\,\alpha^3 > \frac{K^R}{8}. \tag{7.46}$$

Furthermore, if one replaces $\beta = \sqrt{\frac{K^E}{K^R}}$, one can write the inequalities (7.45) and (7.46) as:

$$f(\beta) = \beta^3 + 3\beta^2 - 5\beta + 1 > 0 \tag{7.47}$$

$$g(\beta) = \beta^3 - 5\beta^2 + 3\beta + 1 < 0. \tag{7.48}$$

To end up with an innovation mode one needs $f(\beta)$ to be a positive value and $g(\beta)$ to be negative. To illustrate where these two conditions can hold simultaneously, the values of β are drawn and examined in Figure 7.9.

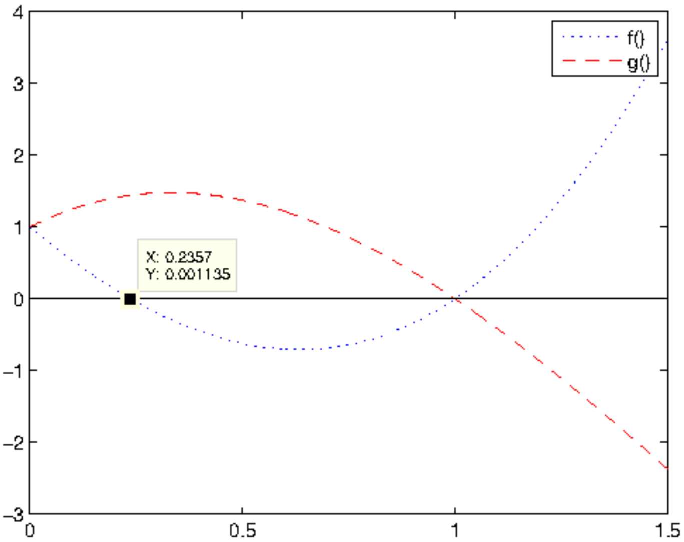


Figure 7.9: f and g functions of β

It is seen that both of the conditions for the innovation mode hold only when $\beta > 1$, which means when $K^E > K^R$. However, this would mean that the innovation should make the price of electricity higher, which is in line with the result found in the first part. In addition to that, it is observed in Figure 7.9 that for very low values of β (i.e., $\beta < 0.236$, which means $K^E < 0.056K^R$), inequality (7.47) can be satisfied. However, this partial satisfaction of the conditions does not suffice to be able to leave the status quo state since inequality

(7.48) is also required to hold for a partial innovation mode. Thus one can conclude that although demand mobility towards the innovating generator supports the case in favor of the innovation mode, it would not change the result. A decrease in cost of electricity for the generator, which would eventually drop the wholesale price of electricity, is a compelling loss which cannot be balanced by a shift of demand from the non-innovating generators. The case would hold for an oligopoly market with multiple generators.

Note that some important assumptions are made to arrive at this result. First of all it is assumed that the companies offer their generation capacities at their marginal cost. Although this assumption does not rule out a possible markup on the price, it rules out the use of market power to bid much higher prices than the cost of generation. For a situation in which the innovating generator can pose higher prices without losing customers, the innovating generator can avoid price drops while enjoying a cheaper generation with a cost-cutting generation technology.

Another important underlying assumption is that some supply cost curves (K) are assumed for each generator. This implies that the generators are large-scale enterprises that provide not only one type of generation but a mix of generation supply with different capacities and costs that can be approximated as a supply curve. For markets with smaller generation enterprises, some discrete functions of supply curves are required, which contradicts with our modeling approach. Thus small generation companies, which are excluded in our model, might change the situation in favor of the innovation mode.

7.4 Conclusions and policy implications

Innovation in electricity sectors is a prominent topic as the energy sources are becoming scarce and demand for cleaner energy is growing. The electricity sector, which is notoriously slow to innovate, needs to renew itself. Especially the industry needs new electricity generation technologies, which are examined closely with a game theoretical model in this chapter.

In this chapter innovation in electricity sectors, specifically technology innovation in electricity generation technologies, is examined. It is argued that there is limited innovation in electricity sectors, and the nature of the problem is discussed extensively. The characteristics of the industry that hinder the innovation are discussed. Consequences of the limited innovation in the electricity sector are highlighted. First, the innovation-related characteristics of electricity supply and generation systems such as economic criticality, spatial scale, inelasticity of electricity demand and capital intensiveness are discussed. It is argued that the functioning of the electricity sector is highly critical for the economy as well as for society and has to be safeguarded at all times, posing a constraint on experimentation. Even in highly liberalization oriented countries, states have to regulate the market to protect the functionality of the system. Overarching institutions are needed to coordinate and encourage innovation, which can be difficult to form especially in politically fragmented Europe.

The ‘quality’ of electricity has become a significant concern lately. Although electricity is classically considered to be a featureless commodity, with the rise of concerns regarding green house gas emissions and global climate change, ‘clean energy’ has found a prominent place in the terminology of the energy industry as well as in the main stream media. Consequently, ‘clean electricity’ has found a place in the portfolio of energy providers and retailers.

We put forward the hypothesis that demand response to the ‘quality’ of electricity makes it easier for generators to engage in innovation mode. In the case of electricity, demand is so inelastic that many innovations do not take off, since the demand response to the quality of the electricity is minuscule. An assessment of so called ‘green energy’ in conjunction with the demand responsiveness of the electricity demand side is made. The green energy concept does not extend into public awareness as much as desired, despite the large amount of green energy buzz in the media. Any investment in a change in the electricity sector is capital-intensive and thus difficult to realize. The question of who would pay the cost is always raised. As a result, rather than private institutions, states get involved in providing innovation boosts. However, whether state funding for innovation is enough for an innovation take off is still questionable. New and cheap generation technologies can potentially mean cheaper electricity, which can inhibit the revenues of the generators.

To test the economical and strategic relationships between the actors in the system, game theoretical formal models are suggested as a method for analyzing incentive mechanisms and individual interests. A game theoretical model that conceptualizes technology innovation in electricity supply industries is formulated. This model conceptualizes the R&D spending of the generator companies and examines whether they have the right incentives to invest in innovation. Generation companies, equipment vendors and retail companies are modeled in this game. In the first part of the model, a generation company and an equipment vendor play a game of investment. This part of the game shows that for innovation to take off, the generator should either gain more demand due to the innovation or the innovation should inflate the price of electricity. This assertion is shown to hold true even if the innovation costs are fully subsidized. Thus, as discussed earlier, demand response to innovation is confirmed to be a key factor for innovation to pick up.

The first part of the game theoretical model focused on a single company. Hence the effect of cheaper electricity to attract customers of the other generators was ignored in this part. The second part of the model expanded the first part to a duopoly generation game. In the duopoly game, the generators again considered engaging in an innovation mode. In this case, dropping prices of electricity, hence decreasing revenue for an innovating generator, could be offset with an increase in customer base due to cheaper electricity. However, the analysis showed that the result does not change much for the duopoly situation, either. One could expect similar results from an oligopoly expansion of the model as well.

The analysis claims that competition alone cannot bring automatic innovation into electricity markets. The association of innovation with competition stems from various free market examples of ‘conventional’ goods and services such as consumer goods or hospitality services. However, we argue that in these sectors the quality of the good matters enormously for the consumers. Consumers react to novel goods and innovative services. However, if there is not enough demand response to innovation, the innovators have a hard time in selling their novelties. Another point that makes the electricity generation sector different than these conventional businesses, is the effect of innovation on the price of the good or service. A novel cell phone can be sold for a higher price, at least momentarily, whereas in the electricity sector, no consumer wants to pay more for a new type of electricity. If the new technology does not increase demand, then it should not make the electricity cheaper. The cheaper electricity could potentially lead the electricity companies to existential crisis.

There is also the issue of capital-intensive costs associated with investment in novel technologies in electricity generation, conceptualized by parameter θ in our model. Governments might be able to help generators to bear these high costs of investment through various price incentives such as tax credits or subsidies. However, even then, decreasing energy prices are a major risk for generators to engage in an innovation mode.

It is important to underline that generators are assumed to have quadratic cost functions while obtaining these results. This assumption is a feasible one for a duopoly market. However, for a perfect market with many small generators, a different model needs to be considered. An oligopoly game and a perfect market game, which would contain a large number of small generators, remain as a possible follow-up to this study.

Considering all aspects of the innovation in the electricity generation sector and the electricity industry in general, one can conclude that one cannot rely solely on the market for the much needed new technologies in the electricity generation industry, at least not in oligopolistic markets. Our game theoretical model shows that generators will not invest in generation technologies that can potentially bring their profits down or that do not increase demand for electricity.

Chapter 8

Policy Synthesis and Reflections

In the previous three chapters, three different cases of strategic behavior in the context of liberalized electricity sectors were analyzed. Each of these analyses implied different policy implications regarding the particular strategic issues presented. While conducting these analyses, we employed game theoretical formal modeling as the methodology, as explained in Chapters 3 and 4. In this chapter we aim to provide our reflections on the course of the study through various dimensions of the study such as the methodology of the research, insights provided by the outcomes, the policy relevance of the subjects and the actionability of the results.

The goal of the chapter is three-fold. The first one is to synthesize the insights obtained from the three cases in this thesis. By doing this, the aim is to consolidate the learning points to reflect on the strategic behavior in liberalized electricity sectors at a general level. The second goal of the chapter is to provide some reflections on the game theoretical formal modeling methodology employed throughout the research. The third goal of the chapter is to reflect on the actionability of the results of such formal models, specifically game theoretical formal models, in the policy context. The insights about the actionability and use of game theoretical formal modeling are further discussed in light of the study.

In order to meet the goals specified above, some reflections on the study are presented in this chapter. In addition to these author reflections, a number of practitioners who have relevant field and scientific expertise have also been interviewed for their opinions on the various policy implications of the research. These interviews aim to provide some external validation for the use of formal modeling methodology, specifically the game theoretical formal modeling, in analyzing the strategic relationships in liberalized electricity sectors. The analysis of these interviews is presented throughout the chapter in support of the reflection goals mentioned above.

Below is the list of the consulted interviewees:

- Prof.dr. Machiel Mulder: *Professor of Regulation of Energy Markets at Rijksuniversiteit Groningen* and *Regulatory Economics Specialist at Netherlands Authority for Consumers and Markets (ACM)*
- Prof.dr.ir. Margot Weijnen: *Professor of Process and Energy Systems at TU Delft*
- Dr.ir. Laurens de Vries: *Associate Professor of Energy and Industry at TU Delft*

- Dr.ir. Rudi Hakvoort: *Strategy & Regulation Expert for Utilities, ex-Energy Network Regulation Manager at ACM*

Throughout the chapter, the interviewees are kept anonymous and therefore no direct references to the statements.

8.1 Policy synthesis and reflections on policymaking

Throughout the thesis, three cases that concern strategic behavior in liberalized electricity sectors are discussed. This section aims to consolidate the results obtained so far to reflect on strategic behavior in liberalized electricity sectors. However, first the bridge between the theoretical results obtained and the real-life correspondences of these problems is built.

In Figure 4.1 of Chapter 4, where the modeling cycle is presented, a distinction between the real world and the conceptual world was made. The conceptualization phase of the modeling cycle captures the real-life issue into the conceptual world. In the conceptual world, the modeler analyzes the issue in an isolated and safe environment which has no direct consequences in the real world. In general, the modeler arrives at various conclusions with the model analyses in this isolated environment. The conclusions can be vivid and detailed with respect to the conceptualized world and scenario. However, this does not mean that the same vivid and clear-cut conclusions are valid with the same confidence level in the real-life. In the policy recommendations phase, where the conclusions of the modeling work are related to the real-life, one should be aware of various differences between the conceptual world and the real world.

Some of these differences between the real world phenomena and the conceptual phenomena are discussed in the case chapters. The differences mentioned earlier are usually based on the assumptions made for the modeling work, and their implications for the external validity of the results are obtained in the conceptual world. This type of validity aims to bridge the assumptions of the modeling work and real-life. Together with the internal validation of the models, which is concerned with the compliance of the modeling reasoning and consistency of the mathematics of the modeling work itself, these two validations are crucial for a modeling study. However, the external and internal validations do not guarantee the actionability of the policy recommendations. Actionability is more concerned with the appropriateness and the usefulness of the policy recommendations in real-life.

In this section, the real-life actionability of the results obtained in the case chapters is discussed. Furthermore, whether the issues that constitute the subject of the cases of this research are real concerns for the policymakers and whether the results obtained in these cases can be applicable are discussed. In support of the argumentation and for the sake of external validity, some academics and professionals who deal with policymaking and energy modeling are consulted, as indicated in the previous section.

8.1.1 Strategic behavior as a concern for policymakers

Is adverse strategic behavior a real concern for policymakers? The answer to this question is a straightforward “Yes!”, as it is evident in many cases in the liberalized markets. The concern has been manifested in various occasions, such as in the Enron case in which Enron was found to be the culprit of the Californian blackouts of the year 2000 and with Eon and GdF Suez being fined heavily in 2009 due to collusion charges.

But the question could be reformulated in a narrower way: “Is all adverse strategic behavior a concern for policymakers?” An interviewee thinks the answer is conditional to the impact of the misbehavior: “If the effects are serious and the policies do not get the intended results. It is their [SO: policymakers’] responsibility. They have to be concerned. If they are not, then the public opinion, thus the Parliament would push the market authorities.” The interviewee completes this comment by stating that “There will always be the strategic use of rules.”

Actually, this is one of the observations that was made while researching strategic behavior in liberalized electricity markets. It seems that there might always be some strategic use of the rules. However, the question is whether the effects of the particular strategic use is large enough or not to trigger the public and hence the policymakers concerned. If the shortcomings of a particular strategic behavior are harmful on a large scale, the policymakers become concerned and are able to track down the market players’ behavior as being the source of the harmful result. Another interviewee supports this view with the following statement: “It is difficult to prove the strategic behavior. However, in some markets everybody knows that there is some market power. The issue is how market power is used. If market power is used for public benefit then it is tolerated. For instance, ENDESA in Spain and EDF in France are known to have market power. They are monopolists with monopolist rents, but as a public company they are believed to use the power for the benefit of the public.”

Another important observation that is made in this thesis is about the relationship of strategic behavior with demand inelasticity. Electricity sectors are notorious for having inelastic demand. Demand elasticity is an important characteristic for a healthy operation of a free market. Consumers should react to the electricity prices to ensure the healthy pricing of electricity. One of the interviewees underlines the importance of the demand elasticity as follows: “We realized game situations in the power sector, too. If there is enough demand elasticity, it would be more difficult, but there is almost no demand elasticity, which makes the sector prone to market power abuse. The players can make use of the technicalities in the balancing market, spot market and congestion management or a combination of these strategically for their own benefit. You have to model all these to analyze at least some of the strategic behavior.”

Additionally, another interviewee also highlights the importance of real time prices, which are intended to increase price elasticity for the sector, as follows: “The real problem for the competition authority is that consumers do not face real time prices. This [SO: real time pricing] is where the policy focus is. Privacy is the concern of the Parliament, too.”

8.1.2 The policy relevance of the load-shifting problem

The first case, which is presented in Chapter 5, highlights potential free riding behavior in the retail electricity market where load-shifting price incentives are concerned. As a result of this study it is stated that load-shifting price incentives, i.e., the night-time prices that aim to stimulate consumers to shift their load to night-time, should be coordinated. This study shows that market itself does not provide the right incentives to the market players to apply sufficiently low prices at night-time. The retail companies try to free ride on each other's price incentives, which results in a downswing of these incentives. According to our model, in the case of too many retail companies, the defined price incentives (i.e., the price difference between day-time and night-time tariff) drop even to zero.

The analysis shows that a mandatory price difference between the day-time tariff and the night-time tariff could solve the issue for the benefit of all participants including the retail companies. The prices can be left to the market, as should be the case in a free market. Only the price difference between day-time and night-time should be regulated.

On the other hand, policymakers are not pressed on this issue. Moreover since regulation of anything related to tariffs is seen as a taboo in neo-liberal ideology, regulating the price difference does not have top priority. An interviewee states this fact with the following sentences: "Night tariffs are not a desk topic of policymakers. Tariffs are left to the market after the liberalization. So this discussion is not among the responsibilities of the policymakers. However, if this concerns other pressing issues such as greenhouse gas emissions, the topic could be more interesting to policymakers."

In fact, load-shifting would increase the efficiency of the whole system, which translates unequivocally into lower energy costs and may even translate to less greenhouse gas (GHG) emission as the base load is increasingly matched with greener energy. Typically, base power sources are coal-fired, nuclear and hydroelectric, which have the general characteristic of being cheap to run. While hydroelectric and nuclear are 'clean' sources with respect to GHG emissions, coal is a notoriously dirty source. On the other hand, the conventional peaking power sources are natural gas, diesel or jet fuel powered plants, which have short start-up times but are more expensive to run. These fossil-based power plants are dirty sources with respect to GHG emissions. Future scenarios show that the base power sources will increasingly be replaced by green sources such as solar and wind power. With regard to GHG emissions, as the peak power sources stay at status quo and the base power sources are replaced by green plants, load-shifting will increasingly help to accomplish the quest of cutting GHG emissions.

The analysis holds up until the point where night-time usage is greater than day-time usage, which is not plausible in the current context and is hence ignored in our analysis. Load-shifting is an important subject that energy authorities should not leave only to the market. As stated earlier, incentive price regulation would mean an added value not only for consumers and the general welfare but also the market itself. Price incentive regulation would create a win-win situation between the public and the market.

8.1.3 The policy relevance of the congestion management problem and the financial transmission rights case

Financial Transmission Rights (FTR), which is a congestion management technique, is analyzed in Chapter 6. FTR is a promising technique readily in use in various transmission networks in the United States and has some promising features for the pan-European network, where various sorts of congestion management techniques are applied.

The strategy-proneness of FTR is discussed in Chapter 6 in a scenario. The main conclusion of this case was that a generator can take the advantage of private capacity expansion information and manipulate the future FTR prices for its own benefit. The conclusion shows that time is an important aspect in trading FTR, as future prices can be manipulated with the actions executed at present time. One of the interviewees agrees on this point with the following statements: “The big problem with congestion management and specifically with FTR is that it is so time-allocation dependent that you have to study the network to determine whether a generator actually has market power over a particular FTR. That depends on many factors, such as parallel flows, line loads and specific market mechanics. So you have to make a tailored analysis for each network. Models are useful in making this sort of analysis.”

Another important observation is that there are various congestion management algorithms, which are sometimes very similar to each other and sometimes not. In fact a comprehensive benchmark analysis of the mentioned congestion management techniques could be interesting academically. An interviewee also raises this point: “Different member states have different congestion management approaches. A comparison of these could be interesting.”

The real-life developments regarding the FTR and the congestion management are highly active. The EU-wide internal electricity market has been developed progressively since 1999. Especially after the Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity, the progress in creating the internal market has gained momentum. With Regulation (EC) No. 714/2009, in order to ensure optimal management of the electricity transmission system and to allow trading and supplying electricity across borders in the Community, a European Network of Transmission System Operators for Electricity (ENTSO-E), was established. The EU electricity grid operators’ body, ENTSO-E, has been working to increase cooperation and coordination of the national grids.

The aspiration for single electricity market within Europe is a long-standing wish. However, the current situation is far from this ideal, as the issue at hand is still to develop national markets rather than couple them. Meanwhile, the Commission states appreciation for increased interconnector capacities such as the recent Central Western European market coupling. As mentioned in the introduction chapter, liberalization in electricity sectors is an ongoing experiment that has never before been experienced on such a large scale. To illustrate this, it is worth mentioning that with the participation of Germany, the Central Western European market (the Netherlands, Belgium, France) would become the largest market in the world, surpassing PJM, which is currently the largest (Meeus and Belmans, 2008). A future pan-European market would certainly be larger still and many associated challenges lie ahead in direct proportion to its size.

As for the national markets, even before 2000 wholesale power exchanges such as Nord Pool Spot in Scandinavia (Norway, Sweden, Finland, Denmark, and Estonia), APX in the Netherlands, OMEL in Spain and the England and Wales Pool existed. After 2000 several new exchanges such as LPX and EEX in Germany, UKPX in the UK, and PPX in Poland have come into existence. The evolution from national electricity production to power exchanges has occurred seamlessly and the new regulation has been smoothly adopted.

Power exchanges require more capacity to be able to broker the above-mentioned national or regional markets. Ideally, the liberalization process aims for economic efficiency via increasing competition and creating perfect markets. A perfect market must have some key properties, such as no market power and easy access to production. To meet both of these crucial characteristics of a perfect market, building more capacity between the markets is necessary.

In most European markets one or two generation companies dominate the market as previously shown in Table 2.1. These are usually former national incumbents and have considerable market power to game the prices. To increase the number of participants in the market, international trade is a key factor to be established via increased interconnector capacities. Concerning the convergence of the prices in Europe, interconnector capacity is the toughest challenge ahead. In 2002 the European Commission agreed on a target for Member States to reach a level of electricity interconnections equivalent to at least 10% of their installed production capacity by 2005 (Commission et al., 2002a). However this target could not be made by some of the member states, such as the UK, Ireland, Spain and Portugal, even after 2005.

In most of the above-mentioned markets market splitting, or explicit auction in some cases, is the primary congestion management method adopted, with some variations in application. Note that in these markets the market operator implicitly assigns the PTR to the cross-border trading agents. The trade relies on a physical contract-path model. This model would prevail as long as the grid is radial. Meshed structures work to some extent, as long as participation is predictable, such that loop flows can be guessed and ignored or taken into account. If these conditions are not met, this model would be impossible as it would be impossible to partition and allocate the available capacity day ahead. Currently the practice is to forecast and allocate the respective capacity to loop flows. However, with a more complex and liquid market, this would increasingly be more difficult to maintain.

According to some scholars (Duthaler and Finger, 2008), at this point, adoption of FTRs might be the appropriate response to the upcoming challenge of a meshed grid for the emerging pan-European electricity market. According to this model, the TSOs do not sell path-dependent flow-based zonal rights but deliver financial point-to-point rights instead. This model has been employed by various Independent System Operators (ISO), which are the US equivalent of TSO's in Europe, such as PJM, CAISO of California and ERCOT of Texas. Among these, ERCOT used to apply a PTR variant relying on path dependent model.

The preferred way of tackling meshed grid problems is with financial rights. However, some institutional problems such as how to convert from the current system are questions remaining on the table. A more dominant problem is the requirement of close relationship among the involved TSOs. An overarching European institution to coordinate TSOs and market activities is required. Another problem regarding the European wholesale electricity market concerns capacity expansion. For a perfect market, international participation, hence interconnector capacities, must be ample. However, since recently unbundled and dissolved national monopolies had not required international cooperation other than for stability purposes, this is not the case.

More recently, the discussion regarding congestion management in the internal market has been highly active. In fact, in November 2013 the latest version of Network Code on Capacity Allocation and Congestion Management (CACM) was issued by ENTSO-E and progressed through the comitology process, which in EC jargon describes the last stage of legislation before becoming law. The Network Code on CACM sets out the methods for allocating capacity in day-ahead and intra-day time scales and outlines the way in which capacity will be calculated across the different zones and serves as a 'target model' for the design of Europeanelectricity markets. As far as the congestion management algorithms are concerned, The Network Code on CACM suggests two algorithms for the congestion management, namely the 'price coupling algorithm' and the 'continuous trading matching algorithm'. In response, CASC.EU, which is a joint cross-border services company founded by various transmission system operators, i.e., Creos, Elia, TransnetBW GmbH, TenneT TSO GmbH, TenneT TSO B.V, RTE, Amprion, Austrian Power Grid AG, Elektro - Slovenija, Independent Power Transmission Operator S.A., Swissgrid, Terna, Energinet and Statnett, has intiated a project called "North-Western Europe (NWE) price coupling". This cooperation aims to implement a price coupling algorithm for congestion management.

Owing to the recent Europe-wide developments, price coupling algorithms, which imply physical transmission rights as explained in Chapter 6, are becoming a target model for congestion management. One of the interviewees points out this progress as follows: "FTR has been one of the possible candidates for congestion management. These discussions are Europe-wide. The Scandinavian NordPool system used to be a blue print for Europe. However, currently Europe has gone a different direction, i.e., physical rights. ENTSO-E discusses FTR, but I am not sure if they would adopt this in the near future. This topic is clearly a desk-study." FTR could remain a possible candidate in the future, as the development of pan-European congestion management is still in its infancy. Another interviewee agrees on the importance of FTR: "FTR is a relevant topic for policymakers. It provides some good incentives for participants and needs to be analyzed."

8.1.4 The policy relevance of innovation in electricity sectors

Chapter 7 of the thesis analyzes the lack of innovation in the electricity industry. Before the liberalization process, the electricity sector used to be criticized for being slow in innovation. Liberalization and therefore competition was expected to boost innovation in the electricity sectors. In Chapter 7 the current status of innovation in electricity sectors is discussed both descriptively and analytically.

Speaking of innovation, it is important to distinguish the innovation in the supply industry from the innovation in transmission and distribution systems. The descriptive analysis took both generation innovation and transmission and distribution innovation as its subjects.

According to the descriptive analysis and the findings of the game theoretical model, for innovation to take off, the right conditions related to the market should occur. Only under these conditions do the generation companies have the incentive to invest in R&D activities for innovation. These conditions depend on the demand elasticity with regard to the new innovation, i.e., how the consumers would react to a new innovation, the cost efficiency of the innovated power source as well as the cost of the innovation effort. The most important catch of the analysis is to show that competition alone is not an immediate cure for a lack of innovation in electricity sector.

As a policy issue, innovation seems to be beyond the scope of policymakers in liberalized electricity sectors, at least as far as the generation sector is concerned. One of the interviewees states that "Innovation in generation technologies is already beyond the scope of the control of the regulator. Innovation in grid technologies is still within the scope of the regulator, though. The regulator has to sign investments in maintenance, grid expansion or innovation." However, it is important to note that innovation in electricity sectors used to be an issue for policymakers before the liberalization era. The liberalization process was intended to solve the issue of a lack of innovation. Thus it is important to check whether this promise is being fulfilled. Innovation in both generation and the grid should still be a concern for the policymakers as long as this promise is not fulfilled.

In Chapter 7, we show the lagging R&D spending in the electricity sector in comparison to the other sectors as an evidence for lack of innovation in the electricity sector. An interviewee touches upon this evidence as follows: “Investment in R&D is a long-term plan. In the short term there are some developments, though. We rely on the competition between generators for innovation in generation.”

As far as innovation in the grid is concerned, the responsibility of the policymakers is even more imperative. One of the interviewees highlights the role of the regulator in grid innovation as follows: “Regulation makes grid operators innovate. They have a legal responsibility, so they have to transmit the energy in a satisfactory way. The budget for it is limited. They can make profit with innovation. Regulation is second-best after the free market.”

However, the question arising from this comment is that if regulation is already good enough for high innovation, why did a lack of innovation exist during the pre-liberalization period? After all, the national monopolies were regulated government entities.

8.2 Reflections on the methodology

In the previous section, we discussed the policy relevance of the cases that we have analyzed in this research. Moreover, some reflections on the policy part of the study are presented. In contrast to the previous section, this section aims to provide some reflections on the methodology of the research. Game theory, systems thinking and modeling paradigm in general are discussed briefly.

8.2.1 Actionability, generalizability and limitations of game theoretical formal models

The purpose of this subsection is to answer the following questions: Are theoretical models, specifically game theoretical models, actionable in making policy recommendations? Are they generalizable? And what are the limitations?

As outlined in Chapter 3, the research approach of this study imposes building models and developing an internally consistent and externally valid reasoning to answer some policy questions. This mode of reasoning is relatively new and has gained ground with the advent of operations research and high computational power.

Although many of the formal theoretical models, which were built for the purpose of policy analysis, have internal consistency and external validity of the assumptions and results, the questions regarding the actionability of these models are open.

As a general observation it is possible to state that the use of formal theoretical models is limited in comparison to empirical, data-based analysis as far as policymaking is concerned. Even in vital decisions such as court decisions, theoretical models can be of use, although they are usually not self-sufficient. “Both empirical evidence and analytical modeling methods are useful in court. In the merger case of two big energy companies, Nuon and Reliant, a model based on the Cournot’s competition model was used to demonstrate market power. However, the court was not satisfied and asked for empirical evidence. Court officially said several times that they had to look at both the theoretical and empirical evidence. Using only theoretical evidence is not sufficient.”, says an interviewee about this.

The actionability of the models depends on their external validity of the models. Consistency of the results with the known facts of the real-life phenomenon plays an important role in this regard. The answers obtained from the model for a particular question of the policymaker should be consistent with what the policymaker knows about the system. Of course it is important to take the modeling assumptions into account when interpreting the answers of the model. Apart from this point of external validity, policymakers are not particularly interested in the type of modeling employed. One of the interviewees said the following in this regard: "The models themselves are of no use for the policymaker. However, their results can be relevant. What matters more than the modeling approach itself is the attractiveness of the results. Nobody is looking specifically for game theoretical models, they are not an end products. However, the results they can provide matter in policymaking. Policymakers would never contract a model, they would contract an expert." The interviewee further added that "Confidence in the model is built when the model delivers what is expected. The validity of the result with respect to the known behavior is an important way to build confidence into the model. But if the model shows a behavior which contradicts the intuition [of policymakers], the model is useless [for them], because the model is a tool for understanding but it is never the reality. And everybody would know that."

Although the author embraces the importance of the intuition of policymakers, intuitions are never absolute facts. Thus the author thinks that the models, which challenge the intuition of policymakers and scientists alike, should be taken at least as seriously as non-challenging models. The cause of the contradiction with the intuition should be revealed.

Of course, confidence in the model can still be an issue for policymakers, as they do not have the resources such as time and expertise to understand and interpret the model results themselves. "Policymakers listen to the conclusions of the modeling studies but they do not assess the results themselves. Rather, they listen to the middle entities such as the competition authority. The competition authority has access to the experts [SO: such as independent scientists] who can assess these models.", explained an interviewee.

As for the generalizability of the models employed in this study, it is important to be cautious. The models are based on various assumptions and simplifications. These assumptions and simplifications are required for the sake of simplicity of the model. Furthermore, the simplicity of the models is required for the accurate interpretation of their results behind them. The models are generalizable if only one takes the assumptions and simplifications into account and understands the rationale of the model. One of the interviewees addressed the generalizability issue as follows: "As far as the generality of the modeling studies are concerned, there are meaningful differences between countries and type of infrastructures. For instance, for unbundling law, the choices are different in Germany than in the Netherlands."

Indeed, the devil is in the detail. Everybody knows that models are not one-to-one representations of the real-life phenomena. A model is a tool for understanding real-life in the context being explored. The results taken from the modeling work are generalizable only to a limited level. Thus, building overarching theories from modeling work is a limited endeavor. Overarching theories can be built, but one should keep in mind that one size does not fit all in the modeling world. An interviewee underlined this point as follows: "I am a bit pessimistic about the overarching theories of infrastructures. There is too little synergy between different types of infrastructures. For instance, capacity management in electricity is fundamentally different than capacity management in other infrastructures such as transportation, logistics or the internet. The models are different. Being networked alone is not a dominant characteristic to justify overarching theories. However there is room for cross-sectoral learning. At a meta level certain lessons can be learned. For investment cycles, governance of the monopolies, price regulation or output regulation there are some similarities. But it is difficult to talk about generic models." Furthermore the interviewee mentioned that "These models [SO:Game theory or ABM models] are very sensitive for the type of input. Depending on the assumptions you embed in the model, it eill show different behavior."

Thus understanding the model is of utmost importance being able to interpret its results. This point is further elaborated in the next subsection.

8.2.2 Modeling complexities: Stylized models vs large-scale models

In a pursuit to use models in understanding policy problems, preference for small scale, stylized, exemplifying models is made. The 'No-fat modeling' approach of exemplifying theory (Fisher, 1989; Rasmusen, 1994) is elaborated in Chapter 4. Building simple, understandable models makes the models more interpretable. In this regard one of the interviewees also pointed out that simple models are more actionable in the real-life: "Making more complex models does not help to convince policymakers or the courts. If the models are too complicated and difficult to tackle, policymakers do not find them very useful."

Game theoretical models are inherently stylized models with many assumptions and simplifications. As much as the results they provide, the way they conceptualize the real world is important to how they allow us to understand and interpret the results. An interviewee highlighted the distance between game theory and reality in this regard: "There is always a distance between game theory and the reality. Game theory is so abstract that it gives you a mental model framework for what type of behaviors you should be alert to, but it does not play out that way in reality; game theory is too mechanical. But it is good to do these exercises to keep alert to possible behavior."

Nonetheless, it should also be acknowledged that the possible use of large-scale models. Large-scale models, such as Agent-Based Models (ABM), might be more useful when a real-life-like behavior of the model is desired. As opposed to stylized models, in which a limited scope of a particular issue can be addressed, with large-scale, detailed models such as ABMs, it is possible to model various attributes and behaviors with a single model. "ABMs are very rich in terms of smart behavior, smart algorithms for investments or bidding." explained an interviewee.

On the other hand, adding too much complexity and the conceptualization of behavior that corresponds too much to real-life might make the model difficult to trace. One of the interviewees recognizes the use of such black box modeling with a word of caution: "A black box model can also give some results which might be useful for the policymaker. However, people in government would want to know how the results are obtained and what is happening under the hood to some extent. They would never go into the details of your model. They would want to know the underlying methodology. Presenting how the model work is done and how the results should be interpreted is important although the policymakers cannot know the details of the model."

Chapter 9

Conclusions

The final chapter concludes this thesis by summarizing the main results and insights of this research. Also the objectives of the study that were formulated in Chapter 1 are revisited and the answers to the research questions are given in Section 9.2 of this chapter. Furthermore, some perspectives for prospective research topics as an extension to this research are presented in Section 9.4.

Each of the selected cases of this study contains independent actors with their own interests and strategies. The strategies of the actors drive different market results, which are discussed throughout each case chapter. In the load-shifting case in Chapter 5, the decisions of various retailers affect each other and result in a less effective market outcome than in the modeled monopoly case. The second case, in Chapter 6, underlines a strategic advantage for a company due to hidden knowledge. In Chapter 7, it is observed that generation companies do not have the right incentives for innovating low-cost generation technologies, which underlines the role of disincentives in the conceptualized market structure.

Each case chapter and associated thought experiment entails the primary conclusions of this study. Before revisiting the research questions and general objectives of the study, these conclusions of the cases and associated thought experiments are summarized in the following section.

9.1 Conclusions of the cases

The conclusions of the cases can be summarized as follows:

The first case that is studied in this research takes the retail electricity markets as its subject in Chapter 5 and in (Oruç et al., 2010). Specifically the mechanism of load-shifting price incentives applied by the retail electricity companies to the consumers to shift their load from day-time to night time is analyzed. A simple supply chain of the retail electricity market is modeled. In this model, the wholesale market is assumed to be perfectly liberalized, while the number of players in the retail market is left as a control variable. By changing this control variable, monopoly, oligopoly and free market situations of the retail segment of the supply chain are compared. It is found out that retailers in a perfect retail market setting have less incentive to offer price incentives to the consumers in comparison to a monopoly situation.

It is shown that when a monopoly retailer is divided into two or more separate retailers, the independent retailers may decrease their respective price incentive offers in order to cut their costs while still benefiting from the incentive applied by the other retailer. The behavior is identified as free-riding. The theoretical result furthermore suggests that as the number of retailers diverges to infinity, the price incentive converges to null. As a solution to this phenomenon, regulation of price incentives is proposed in Chapter 5 as a policy measure.

Another case analyzed in this study features a particular congestion management scheme in wholesale electricity markets, which is called financial transmission rights (FTR) as in Chapter 6, in (Oruç and Cunningham, 2011) and (Oruç and Cunningham, 2012). FTR is discussed with respect to its strategy-prone characteristics. A game theoretical model of a coupled FTR and electricity market is formulated, and a scenario in which a strategic behavior due to hidden knowledge is presented. It is possible to identify two main contributions of this case. First, it lays down the mechanisms of FTR clearly and provides clear examples of the the workings of it. In addition to FTR, the chapter explains how Locational marginal prices (LMP) are calculated by exemplifying an LMP calculation.

Second, the model demonstrates a scenario of a potential strategic behavior by the generation companies, who are involved in both the electricity market and the FTR market. The scenario shows that building generation capacity alters the value of the FTR associated with almost all the transmission lines in the network. Hence, if a generation company does not correctly disclose its plans for capacity expansion, it can benefit from the privately held capacity expansion information. Therefore, it is concluded that FTR schemes potentially provide a breeding ground for insider trading. As a countermeasure to this type of behavior, generators trading in financial transmission rights markets should be monitored against the use of private capacity alteration plans.

The last case that is analyzed in this research is related to innovation in the electricity sector in Chapter 7 and in (Oruç and Cunningham, 2013). The idea that there is a lack of innovation in the electricity sector is supported by providing lack of R&D spending as the evidence. It is pointed out that this lack of innovation doesn't particularly depend on the lack of competition and liberalization. Rather, the study highlights some particular characteristics of the electricity systems such as spatial dispersion, criticality and demand inelasticity as the inhibiters of innovation. A game theoretical model of innovation in an electricity generation market is provided, in which a simple supply chain of the generation market is modeled. With this model, it is shown that the market should provide the right financial incentives for generation companies for them to invest in R&D. Furthermore, it is shown that the right incentives depend on many factors, including the demand elasticity of the market, the cost of innovation and the cost-effectiveness of the new technology, which in this case is the hypothetical innovation artifact.

According to the model, competition between generation companies for market share by providing cheaper electricity price does not suffice as a boost of innovation. Innovating for cheaper electricity does not work for generators, since theoretically gaining market share through offering lower prices does not justify the lost revenue for the innovating generators, according to the model in this thesis.

The analysis shows that the relationship between competition and innovation should be rethought, as competition alone looks like not to be the cure for innovativeness. "Competition brings innovation" is a superficial assertion that underrates factors such as demand elasticity, economic added value of the innovation and the costs of innovation, which are all important factors in this endeavor.

9.2 Answers to the research questions and revisiting the objectives of the study

Before the main research question, the subquestions that are formulated in Chapter 1 are revisited. The answers to these subquestions will ultimately make the answers to the main question clearer, and therefore the main questions is kept unanswered until the last part of this section.

The first subquestion reads: "What do we mean by strategic behavior?". The answer to this is partly answered in the introduction chapter. In this context, it is emphasized that 'strategic behavior refers to the actions conducted by organizations which intend to influence the market for their own benefit. These actions may have either a cooperative nature with the other organizations in the market for mutual profits, or a noncooperative nature that increases the organization's profits at the expense of the other organizations and the global welfare. Although by definition it is difficult to determine the adversity of strategic behavior, occasionally some strategic behaviors are referred to as 'adverse'. Adversity of strategic behavior is defined in a narrow sense in the case chapters. The detailed conceptual description of strategic behavior is made in Chapter 1.

In Chapter 1, 'network-based' strategic behavior was contrasted with 'regular' strategic behavior, examples of which can be listed as predatory pricing, collusion and adverse selection. In this research both the regular and network-based strategic behavior are exemplified. Each of the three cases involves a particular strategic behavior that falls within the definition of the strategic behavior defined in this thesis. The first case of the study, which analyzes the load-shifting behavior and the price incentives of the retail electricity companies, shows a free-rider problem in game theoretical terms. This case shows that the retail firms do not have the incentive to offer as much price incentive as the monopoly retailer. This strategic behavior has its roots in the structure of the market mechanism and clearly exhibits an example of networked-based strategic behavior. Moreover, the second case, which is studied in Chapter 6, shows that the generation companies can 'game' the market by keeping their capacity expansion plans confidential. That is to say, the companies capitalize on hidden knowledge in this case. If examined closely, it can be seen that the generation firms take advantage of the network configuration to increase the value of some transmission lines, on which they invest in advance. The strategic behavior in this example also shows the characteristics of a networked-based strategic behavior. Finally, the case in Chapter 7 shows that generation companies would invest in innovation only if the right incentives are provided by the market. The right incentives depend on the characteristics of a particular innovation and the demand elasticity of the market. Strategic behavior in this case can be described the 'strategic use of the essential and indispensable nature of infrastructural utilities', since the demand inelasticity takes its root from the indispensability of electricity. The types of strategic behavior tackled in this research also give the answer to one of the other subquestions that is posed in the introduction chapter, which reads: "What examples of strategic behavior exist in liberalized electricity markets?"

Another question formulated in the first chapter is: "Why do we use formal models and specifically game theory?" The answer to this question is given partly by the third and fourth chapters. The liberalization process is a large-scale unprecedented event. Some analysts even consider it to be a very large-scale experimentation. For such a large scale system, experimentation is costly. Making mistakes is pricey, as it is pricey to implement and retract policies. In this context, the utilization of formal models is motivated by the fact that they are inexpensive substitutes for experimentation. Important insights can be gained by formal modeling and analysis rather than a wait and see strategy to assess policies.

As for the choice of game theory, one can refer to the categorization of modeling techniques such as 'actor-focused' formal models and *system-focused* formal models presented in Section 3.4.2 of Chapter 3. It is possible to point out that in general strategic problems are caused by the behaviors of individuals or organizations, i.e., the actors or players. Hence, an actor-centered modeling technique is suitable in modeling strategic behavior. Moreover, game theory has a substantial literature on the strategic relationships of multiple actors, which is capitalized in this study. For instance, games of incomplete information is a prominent line of research in game theory and the hidden knowledge claims in Chapter 6 can be treated along these lines.

One final question formulated in the introduction chapter was related to the audience of the study: "Who is the policymaker?". Throughout the study, policymakers are referred explicitly. However, the question of "Who is the policymaker?" hangs lightly in the air in the cases. This is a deliberate choice, as the term policymaker refers to a hypothetical decision maker who has the responsibility as well as the right to audit the market mechanisms in favor of global welfare. This generic definition of policymaker is preferred for two reasons: 1) to keep the generalizability of the formal models in this study, and 2) to not become lost in the complexities of the policymaking processes in order not to miss the central insights of the models. In fact, in Chapter 8, it is observed that some of these cases are not particularly considered as real-life policy problems in the Dutch context, according to the interviewees who are interviewed in this chapter. For example, load-shifting price incentives are left to the market and is a concern neither for the Ministry of Infrastructure and the Environment nor for the Netherlands Authority for Consumers and Markets (ACM). So the market is believed to handle load-shifting itself. However, as pointed out in Chapter 5, load-shifting may be not handled in a most efficient manner by the market alone and is an important topic that can provide incremental efficiency in the country's power consumption and increase global welfare. Thus, according to this definition, a policymaker would be concerned with such a gain, audit the market accordingly and, if needed, regulate it. A similar discussion can be made for innovation concerns, which is reported to be left to the market.

The responses provided for the sub-research questions in the previous sections of this chapter brings us to the main research question, which is formulated in Section 1.3 of Chapter 1 as:

> *How can we understand potential strategic behavior in liberalized electricity sectors by utilizing game theoretical formal modeling?*

The first question that the main research question entails is a "How?" question which is concerned with the application of game theoretic formal modeling as a methodology to the specified field, i.e., strategic behavior in liberalized electricity sectors. The second question is concerned with the scope of the application of the proposed methodology, i.e., game theoretical formal modeling.

In order to answer the first question, some cases in liberalized electricity markets are analyzed in Chapters 5, 6 and 7. Different segments of liberalized electricity sectors are considered for strategic behavior. These segments and the associated examples of strategic behavior are chosen and analyzed according to some actual discussions in the literature that are related to strategic behavior. The selection of cases is based on the actuality of the discussions in the literature and their suitability for game theoretical formal modeling as explained in Chapter 4. The selected cases of strategic behavior are analyzed primarily using the framework of game theoretical formal modeling. Although there are some important differences in the applications of the methodology in these cases, there are also common points that constitute the answer to the first part of the main question. These mutual points also constitute the answer to one of the subquestions, which reads: "What exactly is the methodology that we utilize in this research?"

Each case is handled first with a descriptive analysis of the strategic issue at hand. The importance of the situation and why it is the subject of that particular analysis is made clear. The literature associated with the strategic issue is reviewed. If applicable, real-life cases of the strategic issue are mentioned.

In line with the descriptive analysis of the strategic issue at hand, the underlying technical subsystem is discussed apart from the institutional/actor subsystem in each case. The mechanisms related to the particular strategic behavior regarding the underlying technical subsystem are conceptualized. Hypotheses regarding how the strategic behavior occurs are formulated.

In addition to the analysis of the system, the actors are analyzed with respect to the strategic behavior and their roles in it. Only the relevant actors in the strategic behavior are conceptualized as the main actors in the models. Complying with game theoretical thinking, each player is assigned with a payoff function or value. The payoff functions of the players drive their behavior.

Scenarios are utilized to test the hypotheses in this methodology. Some scenarios are formulated after the specification of the models. The behavior is observed and discussed. In some occasions nonintuitive results are obtained. In such cases, the underlying mechanism for such nonintuitive result is tracked and explained. However, in some situations, the results confirm some intuitive or known insights. In any case the main findings are reported, a summary of which can be found in Section 9.1.

The second part of the main research question, which is concerned with the scope of the applicability of the game theoretical formal modeling methodology, is partly answered in the methodological reflections section of Chapter 8. Game theoretical models and the actionability of these models are discussed in this chapter.

9.3 Limitations of the study

Strategic behavior in liberalized electricity sectors is a very broad research field. Several different cases of strategic behavior can be identified, and several different studies with different methodologies can be conducted in this regard. It is inconceivable to consider only a single methodology to tackle problems regarding strategic behavior in electricity sectors.

In this study, game theoretical formal modeling is suggested as a methodology to examine and understand strategic behavior. The methodology, which is discussed elaborately in Chapters 3 and 4, entails various limitations that can be acknowledged.

First of all, it is important to make clear that the models used in this thesis do not attempt to replicate real-life behavior. They are intentionally kept simple, in line with the ‘exemplifying theory’ approach elaborated in Chapter 4. Essentially, the crucial variables and mechanisms of the examined behavior are conceptualized and the remaining variables are considered as not changing. This *ceteris paribus* condition that is applied, together with the simplicity approach, occasionally raise important limitations in the applicability of the results. As an example, the day-time price fixing assumption in the load-shifting case in Chapter 5 is an assumption applied in order to keep the model simple and focus on the night-time discount. However, this assumption can be contested as a crucial one for the dynamics of the model.

It is important to note that the models in this thesis are not the ultimate models that represent the phenomena they are examining. As described in Chapter 4, models are built recursively and there is always room for alteration. With every iteration, there is a trade-off between understandability and accuracy. Complicated modeling for the sake of accuracy of the model can contradict with exemplifying modeling for the sake of understandability. In this thesis the author leans towards exemplifying modeling with a conviction that with exemplifying modeling one can always build an understanding of the phenomenon in focus by at least debating and walking through the model. In contrast, many complicated models are inaccessible, black box models for the audience which demand a lot of time and effort to be understood and debated.

Another problem associated with the results of the study is the generalizability of the outcomes. The results taken from the modeling work can be generalizable only to a limited degree and building overarching results is very difficult. Seemingly similar problems in different contexts can be very different when one uses various variables particular to each case. For instance, congestion management in electricity is fundamentally different than congestion management in gas infrastructures, simply because of the fact that gas can be stored in pipelines whereas electricity cannot.

Moreover, the actionability of the models depends on the external validity of the models and some empirical evidence. One cannot solely depend on the results of the type of models built in this study, but needs external evidence to come to decisive conclusions.

More discussion regarding the actionability, generalizability and limitations of game theoretical formal models can be found in Chapter 8.

Another important limitation of the study is that the author excluded political dynamics among policymakers in the models. In relation to this assumption, the term policymaker’ is used loosely and does not refer to any particular entity, other than a hypothetical governmental organization that regulates the sector. In reality there might be various regulating bodies and these might even be independent from each other. It might even be possible to talk about conflicting interests between these bodies and another level of a game underlying policy decisions. Hence it is important to acknowledge that various structural as well as political dynamics exist among the policymakers in real-life. However, the author opted to exclude the policymakers from the models in order to focus on the technological and institutional aspects of liberalized markets.

9.4 Future research

As it is typical of a PhD thesis, new questions and research topics have arisen during the process of this research. Many of these ideas require an evidence-based analysis to complement the theoretical analysis made in this thesis. This section provides some of these research ideas that could provide follow up to the current research.

In the first case of the thesis, the load-shifting price incentives are analyzed with respect to the competition in the retail electricity market. The study has a theoretical nature. Although the assumptions are based on the real data at times, the conclusions are based on the results of the theoretical model. To complement the policy recommendations that are derived using the theoretical conclusion, a comparative study that analyzes the night-time usage price incentives in different markets would be an interesting extension. How do the load-shifting price incentives in France, where there is a relatively low number of retailers, compare to the load-shifting price incentives in the Netherlands? How do they compare to China, which has a number of different electricity companies that are not under direct control of the government but regulated by SASAC (State-owned Assets Supervision and Administration Commission)? There has been little, if any, research on load-shifting price incentives in relation to market mechanisms in the electricity sector.

Furthermore, in the load-shifting case, some improvements to the model can be achieved. The possible shifts of the consumer portfolios of the retailer can be modeled and taken into account. Moreover, consumers are modeled uniformly, and this could be extended to heterogeneous consumer modeling.

The second case of the study analyzes the Financial Transmission Rights (FTR) in the context of the congestion management mechanisms. A scenario that demonstrates possible strategic behavior is presented in this chapter. This analysis can be extended to the real-life situation in Europe. Furthermore, applied work in the field has only begun. Previous models have emphasized the role of competition. More work is needed on the various applied issues for policy, including identifying sources of market power, modeling specific policy initiatives, and developing distinct problematiques – such as congestion or asset management. Moreover, as one of the interviewees mentioned in Section 8.1, a comparison of different management approaches in congestion management could be interesting.

In Chapter 7 the innovation in liberalized electricity sector was analyzed. The lagging R&D spending in comparison to other sectors was shown as evidence to demonstrate the reluctance to innovate in electricity generation sector. In order to reinforce this argument, one could analyze the innovation trends together with the innovation spending in the pre- and post-liberalization periods. Such an empirical analysis would further ground the theoretical findings of this research.

To sum up, the follow up of this research could benefit more from the abundant data with respect to the trends of the electricity sectors during pre- and post-liberalization periods. As pointed out in Chapter 8, the value of the theoretical models and analyses increases with complementary empirical analysis.

Appendix A

Complementarity problems as an engineering systems design framework

A.1 Introduction

Engineering systems design is traditionally conceived as a mono actor, optimization problem. However with the emergence of decentralized decision making that is boosted by the abundance of distributed computing, the need for multi-actor frameworks of engineering design has becoming imperative. Modern engineering systems, such as networked infrastructures, support the exchange of multiple kinds of goods and services. Flows are becoming multi-commodity, multi-modal, multi-sectoral and multi-faceted. For instance, the shipping industry has long been a multi-commodity enterprize. Multi-modal traffic is increasingly being considered, for instance, in the design of rail links. A fusion of technology is leading to multi-sectoral infrastructure, for instance in the dual design of power and telecommunications lines. Multi-faceted infrastructure is leading to an explosion of new consumer options, and new concerns for decision-makers. For instance, consumers may choose ”green” electricity: this formerly homogeneous good grows more diversified as consumers are presented with increasing amounts of information about the environmental impacts of their choices. Thus, network infrastructures are inherently multi-objective in character.

Modern engineering systems are commissioned, designed and built, and utilized by multiple stakeholders. There is no single objective function held in common between these stakeholders; rather, an expression of opposing economic, social or physical forces is a more useful paradigm for expressing network usage. This realization is often a better depiction of system behavior. In network infrastructures – such as highways, airports, water systems, electrical distribution systems – there are always multiple actors making multiple if interdependent decisions. Multi-actor, multi-objective techniques are sought to replace mono-actor, mono-objective ones. This means that many classical optimization techniques such as linear programming are unable to address the multiple use and objectives of modern engineering systems on their own.

In engineered systems equilibrium is ever present. Mechanical, thermal, electrical, fluidic – all these systems are engineered for a robustness requirement determined by some specifications. The specifications vary depending on the nature of the environment that the engineered artifact is built or utilized in. For instance, in construction sector requirement of resilience to external disturbances such as earthquakes is different in Japan compared to The Netherlands. However in both cases some specifications are designed and put forward to be hold. The equilibrium concept that guarantees a certain specification is always employed in engineered systems. In addition, social equilibrium is an extremely useful concept that has seen application in both economics and the theory of games. In sections to follow we examine the equilibrium characteristics of network infrastructures, and draw parallels with the complementarity framework for modeling. Inarguably, network equilibrium is an important and useful concept for analysis and design. We do however draw a cautionary note, in recommendations for future research, about the appropriate use of equilibrium analysis.

Fortunately there is a useful, but nonetheless overlooked, technique known as the complementarity problem. The complementarity problem offers considerable promise to infrastructure designers, planners and decision-makers. In the following sections we provide a mathematical framework of complementarity problems and connect it to games. Then we will provide an illustrative example to operationalize the mathematical framework of complementarity problems.

A.2 Formulation of the problem

In these initial derivations we limit discussion to the linear form of the problem – the linear complementarity problem (or LCP). This clarifies the key elements of the problem. In addition, many real world applications are linear or near linear in form. Thus, a linear formulation is a useful guide to implementing more complex system relations.

A.2.1 Basic formulation

The problem is:

Find $\boldsymbol{w} = [w_1, w_2, \ldots, w_n]^T, \boldsymbol{z} = [z_1, z_2, \ldots, z_n]^T$ such that

$$\boldsymbol{w} - \boldsymbol{M}\boldsymbol{z} = \boldsymbol{q} \tag{A.1a}$$

$$\boldsymbol{w} \geq \boldsymbol{0}, \boldsymbol{z} \geq \boldsymbol{0} \tag{A.1b}$$

$$\boldsymbol{w}^T \boldsymbol{z} = 0 \tag{A.1c}$$

The equation (A.1c) implies $w_i z_i = 0$ for all i due to inequalities in (A.1b). This condition points out that at least one of the i^{th} element of vectors $\boldsymbol{w}$ or $\boldsymbol{z}$ must be 0. This condition is named as the *complementary condition* of the system of equations in (A.1)

The set of equations in (A.1) is known as *Linear Complementarity Problem (LCP)* since the variables $\boldsymbol{w}$ and $\boldsymbol{z}$ are linearly linked due to (A.1a) and aforementioned complementarity condition. In other cases, the relationship between the complementary variables characterized by a nonlinear equation, where the formulation is called *Nonlinear Complementarity Problem (NLP).*

The obvious solution to LCP could be a combinatorial solutions that involves all possible vectors that satisfy (A.1c). Note that this would be in exponential time since for $\boldsymbol{w}, \boldsymbol{z} \in \mathbb{R}^n$, 2^n computations are needed for utilization of the combinatorial solution. More educated solutions have been developed such as Lemke's Algorithm or Complementary Pivot Algorithm (Murty, 1988).

A.2.2 Origin in duality theory

Consider the following linear program, where $\boldsymbol{x}$ are decision variables, $\boldsymbol{c}$ parameterizes the objective function, and $\boldsymbol{A}$ and $\boldsymbol{b}$ parameterize the constraints.

$$\begin{aligned} \text{minimize } Z &= \boldsymbol{c}^T \boldsymbol{x} && \text{(A.2a)} \\ \text{subject to } \boldsymbol{A}\boldsymbol{x} &\geq \boldsymbol{b} && \text{(A.2b)} \\ \boldsymbol{x} &\geq \boldsymbol{0} && \text{(A.2c)} \end{aligned}$$

The solution to these equations can be expressed in terms of a set of algebraic equations; indeed, this is the core of the simplex algorithm. Investigation of these solutions to this set of variables reveals a fundamental insight that only the set of linear operations (addition and subtraction) are needed to find the optimum solution.

Furthermore, the derivation of any solution can be exclusively expressed in terms of its slack variables. This fundamental insight leads immediately to the duality theory of linear programming. Furthermore, the use of the dual program is useful since it provides insight into the trade-offs at the optimum, without requiring extensive re-optimization of the problem from scratch (Hillier et al., 1990).

The vector of decision variables $\boldsymbol{x}$ is an optimum solution to the problem if the vector is a feasible solution, and if there is a dual vector $\boldsymbol{y}$. The vector $\boldsymbol{y}$ must satisfy the following equations:

$$\begin{aligned} \text{maximize } W &= \boldsymbol{b}^T \boldsymbol{y} && \text{(A.3a)} \\ \text{subject to } \boldsymbol{A}^T \boldsymbol{y} &\leq \boldsymbol{c} && \text{(A.3b)} \\ \boldsymbol{y} &\geq \boldsymbol{0} && \text{(A.3c)} \end{aligned}$$

A.2.3 Parts of the LCP problem

According to the Strong Duality Property these two objective functions give the same numerical value, that is

$$\boldsymbol{c}^T \boldsymbol{x}^* = Z^* = W^* = \boldsymbol{b}^T \boldsymbol{y}^* \tag{A.4}$$

at the optimal point $(\boldsymbol{x}^*, \boldsymbol{y}^*)$ Hillier et al. (1990). Further we identify the vectors $\boldsymbol{v}$ and $\boldsymbol{u}$ as the *primal* and *dual slack vectors* where;

$$\boldsymbol{v} = \boldsymbol{A}\boldsymbol{x} - \boldsymbol{b} \geq \boldsymbol{0} \tag{A.5}$$

$$\boldsymbol{u} = -\boldsymbol{A}^T \boldsymbol{y} + \boldsymbol{c} \geq \boldsymbol{0} \tag{A.6}$$

These equations embody a set of properties relating a solution to its dual variables, including the weak duality property, the strong duality property, the complementarity solutions property, the complementary optimal solutions property, and the symmetry property (Hillier et al., 1990). If we rearrange primal (A.2) and dual (A.3) systems of equations at the optimal point using *slack variables* in (A.5) and (A.6) then we have

$$\begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{v} \end{bmatrix} - \begin{bmatrix} \boldsymbol{0} & -\boldsymbol{A}^T \\ \boldsymbol{A} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{bmatrix} = \begin{bmatrix} \boldsymbol{c} \\ -\boldsymbol{b} \end{bmatrix} \tag{A.7a}$$

$$\boldsymbol{u}^T \boldsymbol{x} = 0 \;\; \boldsymbol{v}^T \boldsymbol{y} = 0 \tag{A.7b}$$

$$\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{v}, \boldsymbol{u} \geq \boldsymbol{0} \tag{A.7c}$$

Here we use basic variables (e.g. $\boldsymbol{y}$) instead of starred variables (e.g. $\boldsymbol{y}^*$) for the sake of simplicity. Complementarity equations (A.7b) can be verified by utilizing optimality equation (A.4) together with *primal* and *slack variables* (A.5), (A.6).

Now, if we do the following definitions in (A.7)

$$\boldsymbol{w} = \begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{v} \end{bmatrix}, \; \boldsymbol{M} = \begin{bmatrix} \boldsymbol{0} & -\boldsymbol{A}^T \\ \boldsymbol{A} & \boldsymbol{0} \end{bmatrix}, \; \boldsymbol{z} = \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{bmatrix}, \; \boldsymbol{q} = \begin{bmatrix} \boldsymbol{c} \\ -\boldsymbol{b} \end{bmatrix} \tag{A.8}$$

we construct our original LCP form in (A.1).

Let $\boldsymbol{M}$ be a given square matrix of order $\boldsymbol{n}$ and $\boldsymbol{q}$ a column vector in $\mathbb{R}^n$. Our decision variables are $\boldsymbol{w}$ and $\boldsymbol{z}$. Throughout this section we use the symbols $w_1, \ldots, w_n$; $z_1, \ldots, z_n$ to denote the individual variables in the problem. The principal difference between a linear program and a linear complementarity problem is that in an LCP there is no objective function to be optimized. We return to these components later when formulating the parts of a basic infrastructure complementarity problem.

A.2.4 Actor and game formulation

It is less intuitive that this systems representation might also represent an equilibrium that emerges from policies or tactics enacted upon a system by multiple actors. To this end, we relate the LCP to the formal notion of a game (Cottle et al., 2009; Murty, 1988), and the concept of a Nash equilibrium (Fudenberg and Tirole, 1991).

Consider a game in which *player I* has m strategies to play and *player II* has n strategies. Then the payoffs for *player I* and *player II* would be $\bar{a}_{ij}$ and $\bar{b}_{ij}$ respectively when *player I* and *player II* choose i^{th} and j^{th} strategies. Then matrix $\bar{\boldsymbol{A}} = (\bar{a}_{ij}) \in \mathbb{R}^{m \times n}$ and $\bar{\boldsymbol{B}} = (\bar{b}_{ij}) \in \mathbb{R}^{m \times n}$ are the payoff matrices corresponding to each player.

Suppose *player I* chooses i^{th} strategy with a probability of x_i then the column vector $\boldsymbol{x} = (x_i) \in \mathbb{R}^m$ describes the mixed strategy of *player I* whereas $\boldsymbol{y} = (y_j) \in \mathbb{R}^n$ similarly describes the mixed strategy of *player II*. So for example $\boldsymbol{x} = [1,0,0]^T$ means *player I* chooses its first strategy out of its three possible strategies whereas $\boldsymbol{y} = [0.5, 0.5, 0, 0]^T$ means *player II* chooses half of the time its first and half of the time its second strategy out of four available strategies. If *player I* and *player II* choose $(\boldsymbol{x}, \boldsymbol{y})$ pair as their strategies then $\boldsymbol{x}^T \bar{\boldsymbol{A}} \boldsymbol{y}$ and $\boldsymbol{x}^T \bar{\boldsymbol{B}} \boldsymbol{y}$ give the payoffs for *player I* and *player II* for this strategy pair.

We can transform the loss matrices $\bar{\boldsymbol{A}}$ and $\bar{\boldsymbol{B}}$ into $\boldsymbol{A} = (a_{ij})$ and $\boldsymbol{B} = (b_{ij})$ with $a_{ij} = \bar{a}_{ij} + \lambda$ and $b_{ij} = \bar{b}_{ij} + \mu$ where λ and μ are arbitrary numbers. In this case since we can write the following equations

$$\boldsymbol{x}^T\boldsymbol{A}\boldsymbol{y} = \boldsymbol{x}^T\bar{\boldsymbol{A}}\boldsymbol{y} + \lambda \tag{A.9a}$$

$$\boldsymbol{x}^T\boldsymbol{B}\boldsymbol{y} = \boldsymbol{x}^T\bar{\boldsymbol{B}}\boldsymbol{y} + \mu \tag{A.9b}$$

an equilibrium strategy pair $(\boldsymbol{x}^*, \boldsymbol{y}^*)$ of the game $\Gamma(A,B)$ is also an equilibrium strategy pair of the game $\Gamma(\bar{A},\bar{B})$ and vice versa. Thus without loss of generality one can consider $\Gamma(A,B)$ instead of $\Gamma(\bar{A},\bar{B})$ by choosing λ and μ such that the payoff matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are strictly positive.

Nash equilibrium is obtained for a strategy pair $(\boldsymbol{x}^*, \boldsymbol{y}^*)$ when none of the players can unilaterally increase her payoff by altering her own strategy. In mathematical terms this means

$$\boldsymbol{x}^{*T}\boldsymbol{A}\boldsymbol{y}^* \leq \boldsymbol{x}^T\boldsymbol{A}\boldsymbol{y}^* \quad \text{for all probability vectors } \boldsymbol{x} \in \mathbb{R}^m \tag{A.10a}$$

$$\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^* \leq \boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y} \quad \text{for all probability vectors } \boldsymbol{y} \in \mathbb{R}^n \tag{A.10b}$$

Using equations (A.10) we can write the following inequalities

$$\boldsymbol{x}^{*T}\boldsymbol{A}\boldsymbol{y}^* \leq \boldsymbol{A}_{i.}\boldsymbol{y}^* \quad \text{for all } i = 1 \text{ to } m \tag{A.11a}$$

$$\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^* \leq (\boldsymbol{B}^T)_{i.}\boldsymbol{x}^* \quad \text{for all } j = 1 \text{ to } n \tag{A.11b}$$

where $X_{i.}$ denotes the i^{th} row of an arbitrary matrix X.

Say $\boldsymbol{e}_m \in \mathbb{R}^m$ is a column vector with all 1's. Then equations (A.11) can be rewritten as follows

$$\boldsymbol{A}\boldsymbol{y}^* \leq (\boldsymbol{x}^{*T}\boldsymbol{A}\boldsymbol{y}^*)\boldsymbol{e}_m \tag{A.12a}$$

$$\boldsymbol{B}^T\boldsymbol{x}^* \leq (\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^*)\boldsymbol{e}_n \tag{A.12b}$$

Then we can define the slack variables as

$$\boldsymbol{u} = \boldsymbol{e}_m - \boldsymbol{A}\boldsymbol{y}^*/(\boldsymbol{x}^{*T}\boldsymbol{A}\boldsymbol{y}^*) \leq \boldsymbol{0} \tag{A.13a}$$

$$\boldsymbol{v} = \boldsymbol{e}_n - \boldsymbol{B}^T\boldsymbol{x}^*/(\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^*) \leq \boldsymbol{0} \tag{A.13b}$$

Note that since $\boldsymbol{A}$ and $\boldsymbol{B}$ are strictly positive matrices, $\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^*$ and $\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^*$ are strictly positive values which makes the inequalities (A.13) hold.

Defining $\boldsymbol{\xi}^* = \boldsymbol{x}^*/(\boldsymbol{x}^{*T}\boldsymbol{B}\boldsymbol{y}^*)$ and $\boldsymbol{\eta}^* = \boldsymbol{y}^*/(\boldsymbol{x}^{*T}\boldsymbol{A}\boldsymbol{y}^*)$, since $\boldsymbol{e}_m^T\boldsymbol{x}^* = 1$ and $\boldsymbol{e}_n^T\boldsymbol{y}^* = 1$ by definition, one can show that the following equations hold

$$\boldsymbol{u}^T\boldsymbol{\xi} = 0 \tag{A.14a}$$

$$\boldsymbol{v}^T\boldsymbol{\eta} = 0 \tag{A.14b}$$

Using equations (A.13) and (A.14) one obtains the standard LCP form

$$\boldsymbol{w} - \boldsymbol{M}\boldsymbol{z} = \boldsymbol{q} \tag{A.15a}$$

$$\boldsymbol{w} \geq \boldsymbol{0}, \boldsymbol{z} \geq \boldsymbol{0} \tag{A.15b}$$

$$\boldsymbol{w}^T \boldsymbol{z} = 0 \tag{A.15c}$$

where

$$\boldsymbol{w} = \begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{v} \end{bmatrix}, \boldsymbol{M} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{A} \\ \boldsymbol{B}^T & \boldsymbol{0} \end{bmatrix}, \boldsymbol{z} = \begin{bmatrix} \boldsymbol{\xi} \\ \boldsymbol{\eta} \end{bmatrix}, \boldsymbol{q} = \begin{bmatrix} -\boldsymbol{e}_m \\ -\boldsymbol{e}_n \end{bmatrix}$$

Hence as demonstrated the solutions to the LCP problem is functionally identical to Nash equilibrium. If $(\boldsymbol{u}^*, \boldsymbol{v}^*, \boldsymbol{\xi}^*, \boldsymbol{\eta}^*)$ is a solution of the LCP (A.15) then the equilibrium strategy pair can be calculated as

$$\boldsymbol{x}^* = \frac{\boldsymbol{\xi}^*}{\sum_i \xi_i^*}, \quad \boldsymbol{y}^* = \frac{\boldsymbol{\eta}^*}{\sum_j \eta_j^*} \tag{A.16}$$

Thus the two-player bimatrix game $\Gamma(A,B)$ is equivalent to a class of LCP problems.

Many social settings may be expressed in terms of games (Fudenberg and Tirole, 1991). Thus, a game equivalency demonstrates the descriptive possibility for using LCP in a multi-actor setting. Most importantly, a market is also a specific setting of a game, allowing us to model economic questions as well as engineering questions within an LCP framework. Understanding of market equilibrium as an LCP problem seems to originate with Cottle et al. (1970). More recent algorithmic work, which also places market equilibrium calculations within an LCP framework is offered in (Devanur, 2007).

A.3 Illustrative example

Finally we would like to introduce an example to illustrate utilization of complementarity with respect to actor-network perspective. This example is modeled and solved using GAMS (Brook et al., 1988). This proves that network equilibrium problems can be addressed within the capabilities of standard optimization and analysis software.

A.3.1 Problem formulation

In Figure A.1, one can see the network infrastructure that we consider in this example. The example is a generic one. The reader may consider this example as a power transmission problem where the supply nodes represent power plants and the demand nodes represent power consumers. Or the example can be casted as a transshipment problem where a commodity is produced by a company in two cites and planned to be distributed to three respective consumption locations.

Suppose a matrix represents the costs associated with each route from *Supply* to *Destination*. The C_{ij} values depicted in the figure represent these costs. In this case each route is loaded by some load, which is represented with x_{ij}. The problem is how the distribution of loads on the routes take place economically. In other words what are the x_{ij} values that satisfy the given conditions.

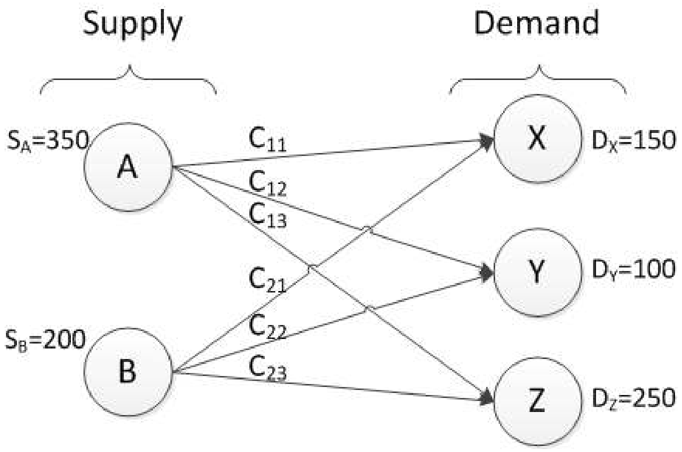


Figure A.1: Infrastructure Network

A.3.2 Complementarity formulation

The linear program associated to this example can be written in the following form:

$$\min_{x\geq 0} \quad \sum_{(i,j)} C_{ij}x_{ij} \tag{A.17a}$$

$$\text{subject to} \quad \sum_j x_{ij} \leq s_i, \quad \forall i \tag{A.17b}$$

$$\sum_i x_{ij} \geq d_j, \quad \forall j \tag{A.17c}$$

Here s_i corresponds to the supply amount at each supply node i and d_j represents the demand amount at each demand node j.

The aim of the market is to spend as little as possible to transmission costs, which is represented in (A.17a). The last two equation here in (A.17) are the conditions for supply and demand respectively. The total amount of supply cannot exceed the supply capacity and similarly total demand in the demand nodes cannot be more than the total actual feed.

For each constraint written above, there exists a multiplier, which corresponds to the marginal prices at each node. The marginal price in this context is sometimes referred as shadow price and constitutes the dual variable associated with each constraint. If we call each marginal price at supply node i, p_i^s and at demand node j, p_j^d then we can write

$$0 \leq p_i^s \perp s_i \geq \sum_j x_{ij}, \ \forall i \tag{A.18a}$$

$$0 \leq p_j^d \perp \sum_i x_{ij} \geq d_j, \ \forall j \tag{A.18b}$$

When the supply at a particular node exceeds the total actual transmission from that node, the marginal price at this node becomes zero as there already exists some excess amount at that supply node. Similarly, as the excess amount is exhausted, the marginal price of a unit of commodity becomes more than zero. Hence marginal price at a supply node and the excess amount at that node are complementary to each other, which makes it possible to write the condition in (A.18a).

A similar argumentation can be made for the proposition in (A.18b).

Another condition that we can derive from the example is that the supply price at i added up to the cost of bringing the commodity from j to i C_{ij} must exceed the market price at j, i.e. $p_i^s + C_{ij} \geq p_j^d$. In case $p_i^s + C_{ij} > p_j^d$ is valid then transmission from source to supply is economically not feasible, hence $x_{ij} = 0$. If $p_i^s + C_{ij} = p_j^d$ then transmission is feasible and $x_{ij} > 0$. In the condition that $p_i^s + C_{ij} < p_j^d$ the system is not stable and it adjusts itself with an increase in p_i^s until it is in equilibrium again. Thus we have the condition of $p_i^s + C_{ij} \geq p_j^d$.

In summary all the complementarity conditions discussed above can be written as follows;

$$0 \leq p_i^s \perp s_i \geq \sum_j x_{ij}, \ \forall i \tag{A.19a}$$

$$0 \leq p_j^d \perp \sum_i x_{ij} \geq d_j, \ \forall j \tag{A.19b}$$

$$0 \leq x_{ij} \perp p_i^s + C_{ij} \geq p_j^d, \ \forall (i,j) \tag{A.19c}$$

The above mentioned conditions determine a complementarity problem and can be solved by a standard PC. We utilize GAMS (Brook et al., 1988), which is a well recognized optimization software that can solve complementarity problems as well as optimization problems. Without giving syntactic details in application of the above formulated problem we give the results to our basic problem in the following subsection.

A.3.3 Basic problem results

Suppose we have the following parameters for the problem that is formulated above and shown in Figure A.1:

$$c = \begin{bmatrix} 5 & 15 & 10 \\ 10 & 5 & 25 \end{bmatrix}, \ s = \begin{bmatrix} 350 \\ 200 \end{bmatrix}, \ d = \begin{bmatrix} 150 \\ 100 \\ 250 \end{bmatrix}$$

Here the costs associated with every arc is given and the supply and demand amounts are fixed numbers.

Coding complementary conditions that are formulated in the above section in GAMS, the following solution is obtained:

$$x = \begin{bmatrix} 100 & 0 & 250 \\ 50 & 100 & 0 \end{bmatrix}, \ p^s = \begin{bmatrix} 5 \\ 0 \end{bmatrix}, \ p^d = \begin{bmatrix} 10 \\ 5 \\ 15 \end{bmatrix} \tag{A.20}$$

According to this result the *SupplierA* utilizes all the production capacity it has by providing 100 and 250 units of commodity to *ConsumerX* and *ConsumerZ* respectively. However *SupplierB* cannot provide all its capacity. By providing 50 units to *ConsumerX* and 100 units to *ConsumerY*, it is left with 50 units of excess capacity. Hence the marginal price of the commodity on location B is 0, whereas marginal price of producing one more good at location A is 5 units of money.

Similarly since the total procurement to *ConsumerA* and *ConsumerB* meets the respective demands, the marginal price of the commodity in question is positive.

A.3.4 Game formulation

The above described example problem is extended to a game by introduction of a ”ceiling cap” as a policy target and a ”fine charge” as a policy measurement by an authority. This hypothetical problem can be casted as a link capacity problem in an electricity transmission system or a congestion problem in traffic management.

Suppose ”the authority”, being a player in our game, wants to keep the load on each arc below a ceiling target, e.g. $ceiling = 150$. In this case the results for x in equation (A.20) cannot be satisfied since the load from *SupplierA* to *ConsumerZ* is fixed at 250.

To reduce the actual loads to target levels, the authority applies ”fine charge” on the arc where there is a risk of excess load. The ”fine charge” is added to the costs listed in the above c matrix effectively. So the ”market”, being the other player, responds by reducing the load on the corresponding the arcs.

The problem in complementarity form is formulated as follows:

$$0 \le p_i^s \perp s_i \ge \sum_j x_{ij}, \ \forall i \tag{A.21a}$$

$$0 \le p_j^d \perp \sum_i x_{ij} \ge d_j, \ \forall j \tag{A.21b}$$

$$0 \le x_{ij} \perp p_i^s + C_{ij} + F_{ij} \ge p_j^d, \ \forall (i,j) \tag{A.21c}$$

$$0 \le F_{ij} \perp T_{ij} \ge x_{ij} \tag{A.21d}$$

Here F is a matrix representing the fine charges applied on each arc and T being the target values for each arc, which is determined as 150 for our example.

A.3.5 Game equilibrium results

The following values for x, p^s, p^d and F at equilibrium are found:

$$x = \begin{bmatrix} 150 & 0 & 150 \\ 0 & 100 & 100 \end{bmatrix}, \ p^s = \begin{bmatrix} 0 \\ 0.955 \end{bmatrix}, \ p^d = \begin{bmatrix} 7.025 \\ 5.955 \\ 25.955 \end{bmatrix}, \ F = \begin{bmatrix} 2.025 & 0 & 15.955 \\ 0 & 0 & 0 \end{bmatrix}$$

The application of fine by the authority are applied both on $A - Z$ and $A - X$ whereas in the first scenario only $A - Z$ was congested. This is because part of the freed up 100 units on the link $A - Z$ is shifted to $A - X$ and congested this link. However not all the freed up capacity by *ProviderA* is used since *ProviderB* is still more economical in procuring to *ConsumerY*. The congested $A - Z$ line benefited *ProviderB* since now it provides the excess 100 unit that *ConsumerZ* requires. Effectively marginal price in location becomes 0 whereas in location B marginal price becomes positive. The congestion on link $A - Z$ had a negative impact on the marginal price in consumption location Z and pushed the price from 15 to 25.955

Appendix B

Appendix B: Load Shifting Price Incentives MATLAB Implementation

The load shifting case of Chapter 5 contains a computational model of a hypothetical electricity retail market with electricity retailers and consumers involved in a problem of load shifting. The computational model that we framed mathematically in Chapter 5 is modeled with MATLAB. In order not to disturb the flow of the chapter, we did not go into the implementation details of the computation model in the corresponding chapter and left the task to this appendix chapter.

MATLAB is a common computational toolbox utilized mostly by engineers, mathematicians and data scientists to model the real world phenomena and run digital experiments on them. MATLAB code is relatively straightforward in terms of readability. Thus even if one does not understant MATLAB, it is possible to track the programming flow to some extent by tracking its code. Because of this ”pseudo-code flavor” of the MATLAB code, we present the functions used in the model in this chapter;

——main.m——

```
%set the market parameters
alpha=2;
beta=4;
gamma=30;
theta=600;
Q_T=1000;
Q_A=500;
Q_B=500;
x_N=3;

```

```
L=-10:4000;
u=-1:0.01:3.5;
kamil=conscost(alpha,beta,u);
plot(u,kamil)
xlabel('Daily Shifted Load [kWh]')
ylabel('Total Cost of Load Shifting [EUR]')

nearar=proincent(gamma,theta,L);
figure(2)
plot(L/1000,nearar)
xlabel('Daily Total Shifted Load [MWh]')
ylabel('Incentive to Retailer per Consumer [EUR]')
ylim([0, 32.5])

[ru,residual]=fminsearch('findruN',[4,1])

profit_cons=ru(1)*(ru(2)+x_N)-fung(alpha,beta,ru(2))
profitPerC_ret=funf(gamma,theta,Q_T*ru(2))-ru(1)*(ru(2)+x_N)

[ru2,resi2]=fminsearch('findruN',[4,1,4,1 ])

profitz=calc_profits(alpha,beta,gamma,theta,Q_A,Q_B,x_N,ru2(1),ru2(3));
profit_cons2=profitz(1)
profitPerC_ret2=profitz(2)

%multiple retailer case
N_tot=9;
R=[];
U=[];
Res=[];

for i=1:N_tot
    N_x=[];
    for j=1:i
        N_x=[N_x 3.29 0.78];
    end
    options=optimset('TolX',1e-20,'MaxFunEvals',1e20,'MaxIter',1e20);
    [ru_x,residual]=fminsearch('findruN',N_x,options);
    R=[R ru_x(1)];
    U=[U ru_x(2)];
    Res=[Res residual];
end

figure(10)
```

```matlab
title('Incentive (r) change with increasing number of retailers')
plot(R);
figure(11)
title('Incentive (u) change with increasing number of retailers')
plot(U);

%multiple retailer case
prof_ret=[];

xr=1.5:0.01:4;
xno=1:numel(xr);
for r=xr
    profitzz=calc_profits(alpha,beta,gamma,theta,Q_A,Q_B,x_N,r,r);
    prof_ret=[prof_ret profitzz(2)];
end

figure(3)
plot(xr, prof_ret)

profits2=zeros(numel(xr),numel(xr));
profits3=zeros(numel(xr),1);

for ra=xno
    for rb=xno
        kamil=calc_profits(alpha,beta,gamma,theta,Q_A,Q_B,x_N,xr(ra),xr(rb));
        profits2(ra,rb)=kamil(2);
    end
end

    for rb=xno
        kamil=calc_profits(alpha,beta,gamma,theta,Q_A,Q_B,x_N,xr(rb),xr(rb));
        profits3(rb)=kamil(4);
    end

a=find(xr==3.29);
figure(5)
plot(xr,profits2(:,a))

xlabel('Incentive per shifted load applied by Retailer A [EUR/kWh]')
ylabel('Profit per Consumer of Retailer A [EUR/consumer]')
```

```

figure(6)
plot(xr,profits3)

figure(7)
plot(xr,profits3)
```

——proincent.m——

```
function out = proincent(gam,thet,L)
%function of the incentive for each retailer
out=[];
for i=1:length(L)
    kamil=gam*(1-exp(-L(i)/thet));
    if (L(i)>0)
        out=[out kamil];
    else
         out=[out 0];
    end
end
end
```

——findruN.m——

```
function toteqn = findruN (guess)

N= length(guess)/2;
r=zeros(1,N);
u=zeros(1,N);

equ=zeros(1,2*N);

alpha=2;
beta=4;
gamma=30;
theta=600;
x_N=3;
Q_T=1000;

Q_x=Q_T/N;

for i=1:N
    r(i)=guess(2*i-1);
    u(i)=guess(2*i);
end

expo_term=exp(-sum(u)*Q_x/theta);

```

```
for i=1:N
    equ(2*i-1)=r(i)-beta/(alpha-u(i));
    equ(2*i)=gamma/theta*Q_x*expo_term-r(i)-beta*(u(i)+x_N)
        /(alpha-u(i))^2;
end

toteqn=0;
for i=1:2*N
    toteqn=toteqn + equ(i)^2;
end
end
```

——funf.m——

```
function out = funf(gam,thet,val)

kamil=gam*(1-exp(-val/thet));
    if (val>0)
        out=kamil;
    else
         out=kamil;
    end
end
```

——calc_profits.m——

```
function profits = calc_profits(alpha,beta,gamma,theta,Q_A,
    Q_B,x_N,rA,rB)

uA=(-beta+rA*alpha)/rA;
uB=(-beta+rB*alpha)/rB;


profit_consA=rA*(uA+x_N)-fung(alpha,beta,uA);
profitPerC_retA=funf(gamma,theta,Q_A*uA+Q_B*uB)-rA*(uA+x_N);

profit_consB=rB*(uB+x_N)-fung(alpha,beta,uB);
profitPerC_retB=funf(gamma,theta,Q_A*uA+Q_B*uB)-rB*(uB+x_N);

profits=[ rA rB profitPerC_retA  profitPerC_retB , uA, uB,
    profit_consA  profit_consB ];
```

Appendix C

Appendix C: Financial Transmission Rights MATLAB Implementation

——main.m——

```
%Electricity Market parameters
%Gen=[G1;...;GnGen]=[node alpha beta gen_status ; ...]
Gen=[1 150 40 1; 2 150 30 1];

%Load=[L1;...;LnLoad]=[node P_L ; ...]
Load=[3 -100];

%Line=[from to link_reactance link_cap ]
Line=[1 2 1 10000 ; 1 3 1 10000 ; 2 3 1 50];

[P,LMP,LMP_energy,LMP_congestion,Transmission_loads,FTR_rewards,Profit,Revenue,Cost] = ele_market(Gen,Load,Line)

%FTR Market
%Players submit Bid matrices such that the first element represents the
%line and direction (+ or -), te second represents the value, third
%represent the deteoriation factor

theta=0.003;
BidofA=[-1 LMP(1)-LMP(2) theta;3 LMP(3)-LMP(2) theta; 2 LMP(3)-LMP(1) theta];
```

```
BidofB=[-1 LMP(1)-LMP(2) theta;3 LMP(3)-LMP(2) theta; 2 LMP(3)-LMP(1) theta];
BidofC=[-1 LMP(1)-LMP(2) theta;3 LMP(3)-LMP(2) theta; 2 LMP(3)-LMP(1) theta];

Bidof={BidofA,BidofB,BidofC};

[T_out2,FTR_prices2, ProfitFTR,RevenueFTR,CostFTR]=ftr_market(Gen,Line,Bidof,FTR_rewards)
TotalProfit=Profit+ProfitFTR

%PLOTS
nLine=size(Line);
nLine=nLine(1);

nGen=size(Gen);
nGen=nGen(1);

h1=figure(1);
y=[];
x = 0.1:0.1:99.9;
for i=x
    y=[y gen_cost([i ; 100-i],Gen)*[i ; 100-i]];
end

plot(x,y)
hleg1=legend('Total cost with variable  share of generation');
set(hleg1,'Location','NorthWest')

%logarithmic supply function
h=figure(2);
x= -1:0.1:1000;
nsupply=size(Gen);
nGen=nGen(1);
y=zeros(nGen,length(x));
for i=1:nGen
 y(i,:)=supplyfunc(x,Gen(i,2),Gen(i,3));
end

plot(x,y(1,:))
xlimit=1.3*max(P);
xlim([-10 xlimit])
hold
plot(x,y(2,:),'r')
stem(P(1),supplyfunc(P(1),Gen(1,2),Gen(1,3)),'g')
```

```
stem(P(2),supplyfunc(P(2),Gen(2,2),Gen(2,3)),'g')
hold
xlabel('Offered Generation Capacity in Merit Order [MW]')
ylabel('Marginal Cost of Generation Capacity [Euro]')
hleg2=legend('Gen_1','Gen_2');
set(hleg2,'Location','NorthWest')

h=figure(3);

x= -1:0.1:1000;
nGen=nGen(1);
tot=zeros(nGen,length(x));
for i=1:nGen
    for j=1:length(x)
        tot(i,j)=supplyfunc(x(j),Gen(i,2),Gen(i,3))*x(j);
    end
end

plot(x,tot(1,:))
xlim([-10 xlimit])
hold
plot(x,tot(2,:),'r')
stem(P(1),supplyfunc(P(1),Gen(1,2),Gen(1,3))*P(1),'g')
stem(P(2),supplyfunc(P(2),Gen(2,2),Gen(2,3))*P(2),'g')
hold
xlabel('Offered Generation Capacity in Merit Order [MW]')
ylabel('Cost of Generation [Euro]')

hleg2=legend('Gen_1','Gen_2');
set(hleg2,'Location','NorthWest')

h=figure(4);
x= 0:0.1:100;

plot(x, ftr_bid_fun(x,36,0.003))
ylim([35 37])
xlabel('Demanded Transmission Capacity [MW]')
ylabel('Marginal Valuation of the FTR [Euro]')
```

——ele_market.m——

```
function [P,LMP,LMP_energy,LMP_congestion,Transmission_loads,FTR_rewards,Profit,Revenue,Cost] = ele_market(Gen,Load,Line)
    nGen=size(Gen);
    nGen=nGen(1);

```

```
nLoad=size(Load);
nLoad=nLoad(1);

nNode=max(max(Gen(:,1)),max(Load(:,1)));

nLine=size(Line);
nLine=nLine(1);

%choose a slack node (assumption: not a generator, last load node)
slnode=Load(end,1);

%initial solution
P0=ones(nGen,1);

%ineq constraints A,b
%PTDF for gens
PTDF_gen=zeros(nLine,nGen);
for k=1:nLine
    for g=1:nGen
        PTDF_gen(k,g)=ptdf([Gen(g,1) slnode],k,Line);
    end
end

%double sided
PTDF_gen_ds=zeros(2*nLine,nGen);
for k=1:2*nLine
    if mod(k,2)
        PTDF_gen_ds(k,:)=PTDF_gen((k+1)/2,:);
    else
        PTDF_gen_ds(k,:)=-PTDF_gen(k/2,:);
    end
end
A=PTDF_gen_ds;

%PTDF for loads
PTDF_load=zeros(nLine,nLoad);
for k=1:nLine
    for d=1:nLoad
        PTDF_load(k,d)=ptdf([Load(d,1),slnode],k,Line);
    end
end

%double sided
PTDF_load_ds=zeros(2*nLine,nLoad);
for k=1:2*nLine
```

```
        if mod(k,2)
            PTDF_load_ds(k,:)=PTDF_load((k+1)/2,:);
        else
            PTDF_load_ds(k,:)=-PTDF_load(k/2,:);
        end
    end

    %PTDF for load nodes
    PTDF_node_ds=zeros(2*nLine,nNode);
    for k=1:nLine
        for d=1:nNode
            PTDF_node_ds(2*k-1,d)=ptdf([d,slnode],k,Line);
            PTDF_node_ds(2*k,d)=-ptdf([d,slnode],k,Line);
        end
    end

    %b
    b_pos=Line(:,4)-PTDF_load*Load(:,2);
    b_neg=Line(:,4)+PTDF_load*Load(:,2);

    b=zeros(2*nLine,1);
    for k=1:nLine
        b(2*k-1)=b_pos(k);
        b(2*k)=b_neg(k);
    end

    %eq constraints Aeq, beq
    Aeq=ones(1,nGen);
    beq=-ones(1,nLoad)*Load(:,2);

    % Run DCOPF
    options=optimset('TolX',1e-8,'Algorithm','active-set','FunValCheck','on','Display','iter','TolFun',1e-14,'DiffMaxChange',0.1,'TolX',1e-15,'TolCon',1e-24);

    %P: generation dispatches
    %fval: Total cost of production
    %lambda.eqlin: LMP energy component (same at all the loads)
    %lambda.eqnonlin(k): LMP congestion component on kth node

    %A = sparse(full(A));
    %Aeq = sparse(full(Aeq));
    [P,fval,exitflag,output,lambda,grad,hessian] = fmincon(@(P)gen_cost(P,Gen)*P,P0,A,b,Aeq,beq,zeros(nGen,1),
```

```
        Gen(:,2),[],options);

    PTDF=[PTDF_gen PTDF_load];
    Transmission_loads=PTDF*[P ; Load(1:end,2)];

    LMP_energy=lambda.eqlin;
    LMP_congestion=lambda.ineqlin'*PTDF_node_ds;

    for i=1:nNode
        LMP(i)=LMP_energy-LMP_congestion(i);
    end

    Revenue=zeros(nGen,1);
    for i=1:nGen
        Revenue(i)=LMP(Gen(i,1))*P(i);
    end

    Cost=zeros(nGen,1);
    for i=1:nGen
        Cost(i)=supplyfunc(P(i),Gen(i,2),Gen(i,3))*P(i);
    end

    Profit = Revenue - Cost;

    FTR_rewards=[LMP(2)-LMP(1);LMP(3)-LMP(1);LMP(3)-LMP(2)];
end
```

——ptdf.m——

```
function [nu,slackbus] = ptdf(fromto,k,link)
%fromto(1) is the sending node
%fromto(2) is the receiving node
%k is the link that is affected

%number of nodes
n=max(max(link(:,1)),max(link(:,2)));
f=fromto(1);
g=fromto(2);
l1=link(k,1);
l2=link(k,2);

%calculate susceptance
susc=suscept_calc(link);

%determine a slack bus beginning from the last node
i=n;
while(i>=0)
```

```
    if isempty(find([f,g,l1,l2]==i, 1))
        break;
    else
        i=i-1;
    end
end
slackbus=i;

if slackbus == 0
    nu='Not enough node for calculation';
else

    react=susc;
    react(slackbus,:)=[];
    react(:,slackbus)=[];

    react = inv(react);
    react = [react(1:slackbus-1,:);zeros(1,n-1);react(slackbus:end,:)];
    react = [react(:,1:slackbus-1) zeros(n,1) react(:,slackbus:end)];

    nu=react(f,l1)+react(g,l2)-react(f,l2)-react(g,l1);
    nu=nu/link(k,3);
end
```

——suscept_calc.m——

```
function out = suscept_calc(Link)
    %number of links
    a=size(Link);
    a=a(1);

    %number of nodes
    n=max(max(Link(:,1)),max(Link(:,2)));
    out=zeros(n);

    for i=1:a
        for j=1:n
            if Link(i,1)==j
                out(j,j)=out(j,j)+1/Link(i,3);
                out(Link(i,2),Link(i,2))=out(Link(i,2),Link(i,2))+1/Link(i,3);
                out(Link(i,2),j)=out(Link(i,2),j)-1/Link(i,3);
                out(j,Link(i,2))=out(j,Link(i,2))-1/Link(i,3);
```

```
            end
        end
    end
end
```

——gen_cost.m——

```
function out = gen_cost(P,Gen)
    nGen=size(Gen);
    nGen=nGen(1);
    out=[];

    for i=1:nGen
        out=[out supplyfunc(P(i),Gen(i,2),Gen(i,3))];
    end
end
```

——supplyfunc.m——

```
function out = supplyfunc(x,alpha,beta)

    out=zeros(length(x),1);
    for i=1:length(x)
        if x(i)>=0 && x(i)<alpha
            out(i) = -beta*log((alpha-x(i))/alpha);
        elseif x(i)>=alpha
            out(i) = +inf;
        end
    end
end
```

——ftr_market.m——

```
function [T_out2,FTR_prices2, ProfitFTR,RevenueFTR,CostFTR]= ftr_market(Gen,Line,Bidof,FTR_rewards)

    nLine=size(Line);
    nLine=nLine(1);

    nGen=size(Gen);
    nGen=nGen(1);

    nPlayer=length(Bidof);

    uplim=1000*ones(2*nLine,nPlayer);

    player_bids=cell(2,1);
    for i =1:nPlayer
        bids=[];
```

```
        for k=1:nLine
            item=find(Bidof{i}(:,1)==k);
            if (isempty(item))
                uplim(2*k-1,i)=0;
                bid=[0 0];
                bids=[bids;bid];
            else
                bid=Bidof{i}(item,2:end);
                bids=[bids;bid];
            end

            item=find(Bidof{i}(:,1)==-k);
            if (isempty(item))
                uplim(2*k,i)=0;
                bid=[0 0];
                bids=[bids;bid];
            else
                bid=Bidof{i}(item,2:end);
                bids=[bids;bid];
            end
        end
        player_bids{i}=bids;
    end

    %ETA matrix          Line=[1 2 1 500 ; 2 3 1 500; 1 3
        1 50];
    ETA=zeros(nLine,nLine);
    for k=1:nLine
        for l=1:nLine
            ETA(k,l)=ptdf[Line(l,1),Line(l,2)],k,Line);
        end
    end

    %initial T matrix
    %one for positive direction, one for negative
    T0=ones(2*nLine,nPlayer);

    %FTR allocation
    fnonlcon = @(T)ftr_nonlcon(T,ETA,Line(:,4));
    ffun_ftr_obj = @(T)func_ftr_obj(T,player_bids);

    %options = optimset('Algorithm','interior-point');
    options = optimset('Algorithm','active-set','TolFun',1e
        -14);
    [T_out,fval,exitflag,output,lambda,grad,hessian] =
        fmincon(ffun_ftr_obj,T0,[],[],[],[],zeros(6,2),uplim,
```

```
        fnonlcon, options);

    aa=size(T_out);
    T_out2=zeros(aa(1)/2, aa(2));

    for i=1:aa(2)
        for j=1:aa(1)/2
            a=T_out(2*j-1,i);
            b=T_out(2*j,i);
            if a>b
                T_out2(j,i)=T_out(2*j-1,i);
            else
                T_out2(j,i)=-T_out(2*j,i);
            end
        end
    end

    a=size(T_out);
    FTR_prices=-reshape(grad,a(1),a(2));

    FTR_prices3=zeros(a(1),1);
    for i=1:a(1)
        FTR_prices3(i)=max(FTR_prices(i,:));
    end

    FTR_prices2=zeros(a(1)/2,1);
    for i=1:a(1)/2
        if FTR_prices3(2*i-1)>FTR_prices3(2*i)
            FTR_prices2(i)=FTR_prices3(2*i-1);
        else
            FTR_prices2(i)=-FTR_prices3(2*i);
        end
    end

    RevenueFTR=zeros(nGen,1);
    CostFTR=zeros(nGen,1);
    for i=1:nGen
        for j=1:length(T_out2)
            RevenueFTR(i)=RevenueFTR(i)+FTR_rewards(j)*
                T_out2(j,i);
            CostFTR(i)=CostFTR(i)+FTR_prices2(j)*T_out2(j,i)
                ;
        end
    end

    ProfitFTR = RevenueFTR - CostFTR;
```

```
end
```

——ftr_nonlcon.m——

```
function [C,Ceq] = ftr_nonlcon (T,ETA,CONST)
    a=size(T);
    nLine=a(1)/2;
    nPlayer=a(2);

    B=ones(nPlayer,1);
    ETA_=zeros(nLine,2*nLine);
    for i=1:nLine
        ETA_(:,2*i-1)=ETA(:,i);
        ETA_(:,2*i)=-ETA(:,i);
    end
    %C_pos=ETA*T*B-CONST;
    %C_neg=-ETA*T*B-CONST;
    %C=[C_pos;C_neg];

    C_pos=ETA_*T*B-CONST;
    C_neg=-ETA_*T*B-CONST;
    C=[C_pos;C_neg];

    Ceq=[];
end
```

——func_ftr_obj.m——

```
function out = func_ftr_obj(T,player_bids)
%sum of the total bid values of all the players for a given ftr allocation
    nPlayers=length(player_bids);
    out=0;
    for i = 1:nPlayers
        out = out + func_ftr_totv(T(:,i),player_bids{i});
    end
    out=-out;
end
```

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List of Abbreviations

AC	Alternating Current
ABM	Agent-based Modeling
ACM	The Netherlands Authority for Consumers and Markets
APX	Amsterdam Power Exchange
CACM	Capacity Allocation and Congestion Management
CGE	Computational General Equilibrium
CPP	Critical Peak Pricing
DC	Direct Current
DR	Demand Response
DSM	Demand Side Management
EC	European Commission
EEX	European Energy Exchange
ENTSO-E	European Network of Transmission System Operators for Electricity
ESCO	Efficient Service Companies
FERC	Federal Energy Regulatory Commission
FTR	Financial Transmission Rights
GHG	Greenhouse Gases
GT	Game Theory
HHI	Herfindahl-Hirschman Index
IAM	Integrated Assessment Models
ICT	Information and Communication Technologies
ISO	Independent System Operator
LCP	Linear Complementarity Problem
LPX	Leipzig Power Exchange
LMP	Locational Marginal Pricing
LP	Linear Programming
MARKAL	MARKet ALlocation model
MCP	Mixed Complementarity Problem
MPEC	Mathematical Programming with Equality Constraint
NPM	New Public Management
NE	Nash equilibrium
NLP	Non-linear Programming
NMa	The Netherlands Competition Authority
NWE	North Western Europe
OPF	Optimal Power Flow

OPTA	The Netherlands Independent Post and Telecommunications Authority
OR	Operations Research
PHEV	Plug-in Hybrid Electric Vehicles
PPX	Poland Power Exchange
PJM	Pensilvania-New Jersey-Maryland
PTDF	Power Transfer Distribution Factors
PTR	Physical transmission rights
RTP	Real Time Pricing
SASAC	State-owned Assets Supervision and Administration Commission
TOU	Time of Use
TSO	Transmission System Operators
UIOGPI	Use It Or Get Paid for It
UKPX	The United Kingdom Power Exchange
UNCTAD	The United Nations Conference on Trade and Development
WTO	The World Trade Organization

Summary

The electricity sector, like many other networked infrastructures, is seen as an indispensable and integral part of developed economies. The economic growth, quality of life and general wellbeing of modern societies all depend on the smooth, reliable and efficient operation of the electricity system. Poor reliability and low efficiency pose significant capital risks for industries, considerable political risks for politicians, and substantial wellbeing risks for societies. Thus the seamless, reliable and efficient operation of the electricity system serves the benefit of all. For the excellent operation of the electricity system, the excellence of its management is of utmost importance.

Throughout the world, the management of the electricity sectors has been going through a transition for the past three decades. Until the 1980s, the electricity sector was managed by public or private monopolies. These monopolies dealt with all sorts of operations throughout the value chain of the electricity sector – from generation and transmission to distribution, retailing and services. From the very operational level to the level of strategic management, all of these actions were orchestrated within a singular vertically integrated institution. The system could thereby be managed rapidly in case of emergencies. Similarly, it was possible to optimize long term planning: a central board of directors made informed decisions about issues such as generation capacity planning and transmission capacity expansion, based on the diverse data coming from various parts of the value chain within the same vertically integrated institution.

During the late 1970s, the liberalization trend began to extend into the electricity sector, just as it did in various other public sectors, including telecommunication, air transport, postal services, gas, water and rail transport. Nations all over the world have sinceraced to liberalize their vertically integrated electricity institutions, with the goal of creating more efficient and innovative markets out of the 'archaic' electricity sector. The national monopolies have been turned into competitive firms by certain liberalization steps such as unbundling, deregulation, privatization and reregulation. All these steps to create competitive electricity sectors have required a thorough institutional change of their management regimes. This institutional change has triggered severe and unprecedented problems, alongside the intended and targeted advantages. Among other problems, the strategic behavior of the market participants has been a downside of liberalization.

Strategic behavior

OECD (1993) defines ‘strategic behavior’ as follows:

> “[T]he general term for actions taken by firms which are intended to influence the market environment in which they compete. Strategic behavior includes actions to influence rivals to act cooperatively so as to raise joint profits, as well as non-cooperative actions to raise the firms profits at the expense of rivals”

In this research the term is used in a similar sense. Essentially a particular behavior is strategic as long as it intends to influence the market environment for self-benefit. Despite the term is not explicitly negative, some particular strategic behaviors are denounced as ‘adverse’ in this thesis. Although it can be difficult, even impossible at times, to prove a particular strategic behavior as adverse, adversity can be claimed in a narrow sense, especially in formal models where the impacts of the actors can be quantified.

According to the OECD definition, there are two modes of strategic behavior: cooperative and non-cooperative. In capitalist economies, a free market is free as long as the firms abide by the competition rules. Thus there are various ‘don’ts’ that constrain companies. In a market, firms cannot collude to form a monopoly. Collusion between the market participants for mutual advantage at the expense of the benefit of the market is an example of cooperative strategic behavior. Yet cooperative behavior is not the only way to artificially manipulate prices. In electricity markets, withholding generation capacity to push prices higher is one example of non-cooperative strategic behavior. Price predation and the creation of artificial barriers of entry are some other examples. All in all, strategic behavior can have negative connotation from the perspective of the public welfare as well as in term of the health of the market. In the context of electricity markets such behavior may translate into higher prices, less innovation and even severe black-outs.

The belief in the prevalence of adverse strategic behavior can be at times widespread among journalists and public opinion. However, in practice, it is quite difficult to judge a certain behavior as being adverse strategic behavior from a legal and academic perspective. This is mainly due to the fact that it can be very difficult to find evidence. The thin line between strategic behavior and proper competitive behavior is drawn by the intentions of the firm, which are generally not disclosed by the perpetrator of the adverse strategic behavior.

Analyzing strategic behavior is not a straightforward call, even with regard to the non-networked sectors. Adding network complexity makes it even more difficult to analyze networked sectors. Conventionally, market concentration is considered to be an indicator of market power and hence potential strategic behavior. In a perfect market, market concentration is desired to be non-existent and no firm should have the power to manipulate prices. Thus, competition authorities monitor the market concentration to track potential market power abuses. However, since market power is not the only enabler of strategic behavior, market concentration monitoring is not the sole method for understanding and analyzing strategic behavior. The analysis of strategic behavior has to be done with tailored methods that take into account the peculiarities of the underlying system. In this research, this is the electricity system. This study proposes a game theoretical formal modeling approach as a way to analyze strategic behavior in electricity sectors.

Aim and approach of the research

The large-scale change in the institutional and regulatory settings of electricity sectors raises new concerns regarding the interactions of newly emerged actors. Adverse strategic behavior of these new actors has become one of the main concerns for new electricity regimes – in addition to operational and coordination-related concerns. Complexities due to the peculiar characteristics of electricity sectors provide a breeding ground for strategic behavior. Contributing to the understanding of potential strategic behavior in liberalized electricity sectors is the main aim of this PhD thesis.

In analyzing strategic behavior there is no one-size-fits-all method. The characteristics of the sector should be taken into account when analyzing strategic behavior. A modeling approach can be helpful to incorporate the various peculiar characteristics of electricity sectors with market dynamics. Industry-tailored models can help to reveal some potential strategic behaviors. In this research, game theoretical formal modeling was chosen as the methodology to analyze strategic behavior.

The research aims to answer the following main question:

> “How can we understand potential strategic behavior in liberalized electricity sectors by utilizing game theoretical formal modeling?”

The field of this research is liberalized electricity sectors. The Holy Grail of the liberalization process is forming a totally liberalized, self-governing, competitive market, which is unrestrained from corrective government interventions. The transition from national monopolies to liberalized markets is a high-scale, high-cost and unprecedented event. It is highly difficult to conduct trial-and-error experimentation to see the implications of various policies under such circumstances. Any effort to experiment is either infeasible or otherwise very expensive. Due to the lack of experimentation, a natural way to understand and tackle problems associated with liberalization and strategic behavior is to model the system mathematically and computationally. Mathematical and computational models and simulations are cheap alternatives to real-life experimentations, and unexpected insights into the concerned problems might be obtained. Moreover, emerging multiple actors in electricity sectors whose potential strategic behavior is of interest suggests game theory as a suitable choice of modeling approach since game theory can be defined as the study of the interactions of multiple actors. Thus, game theoretical formal modeling is the method applied in this research to analyze potential strategic behavior.

Cases: Thought experiments

The electricity sector is comprised of two main markets: the retail market and the wholesale market. In each of these markets various types of strategic behavior might occur. In this thesis, each of these markets are considered, and a potential strategic behavior is exemplified in each of them. Additionally, the innovativeness of electricity sectors is considered since initially the lack of innovativeness of pre-liberalization era electricity sectors has been shown as one of the strong arguments in favor of liberalization. Each of the three cases analyzed in the thesis contains an original game theoretical model to explore potential strategic behavior.

Load-shifting price incentives in retail electricity markets is the subject of the first case, which is analyzed in Chapter 5. In Chapter 6, financial transmission rights as a congestion management method is analyzed and potential strategic behavior is exemplified. The model of this chapter also includes a model of the wholesale electricity market. Finally in Chapter 7, technology innovation in the electricity sector is discussed. Specifically, a game theoretical model of generation technology innovation is presented, which helps to make some conclusions regarding the relationship between technology innovation in the electricity sector and competition.

Case 1: Load-shifting price incentives in retail electricity markets

The first case described in this thesis has the retail electricity markets as its subject. Specifically, the mechanism of load-shifting price incentives applied by retail electricity companies to the consumers to shift their electricity load from daytime to nighttime is analyzed. A simple supply chain of the retail electricity market is modeled. In this model, the wholesale market is assumed to be perfectly liberalized, while the number of players in the retail market is left as an exploratory variable. By changing this exploratory variable, monopoly, oligopoly and perfect market situations of the retail segment of the supply chain are compared. It is found that the retailers in a perfect retail market have less incentive to provide price incentives to consumers as compared to in a monopoly situation. It is shown that when a monopoly retailer is divided into separate independent retailers, the retailers tend to decrease their respective price incentives to cut their own costs while still benefitting from the incentive applied by the others. Hence, a free-riding effect is observed. Furthermore, the theoretical result suggests that as the number of retailers increases, the optimal price incentive that the retailers would offer converges to null value, assuming the customers do not switch retailers. As a solution to this phenomenon, regulation of price incentives is proposed as a policy measure.

Case 2: Financial transmission rights as a congestion management mechanism

Another case, which is analyzed in this thesis, features a particular congestion management scheme, called Financial Transmission Rights (FTR). FTR is discussed with respect to its strategy-prone characteristics. A game theoretical model of a coupled FTR-electricity market is formulated, and a scenario in which a strategic behavior due to hidden knowledge occurs is analyzed in this case. There are two main contributions of this case. First, it lays down the fundamentals of FTR clearly and provides vivid examples of it. Together with FTR, the chapter explains how Locational Marginal Prices (LMP) are calculated and exemplifies LMP calculation. Secondly, the case demonstrates a scenario of potential strategic behavior by the generation companies. The scenario shows that building generation capacity alters the value of the FTR associated with some of the transmission lines in the network. Hence, if a generation company does not properly disclose its plans for capacity expansion, it can benefit from the privately held information. As a countermeasure to this type of behavior, the generators that trade in FTR markets should be monitored against the use of private capacity alteration plans.

Case 3: Technology innovation in the electricity sector

The last case that is analyzed in this research is related to the innovativeness of the electricity generation sector and is decribed in Chapter 7. The idea that despite liberalization there is a lack of innovativeness in the electricity sector is supported by providing a lack of R&D spending as evidence. It is pointed out that this lack of innovation does not particularly depend on the lack of competition. Rather, the study highlights some particular characteristics of the electricity system, such as demand inelasticity, as the inhibitors of innovation. A game theoretical model of technology innovation in the generation market is provided, where a simple supply chain of the generation market is modeled. With this study, it is demonstrated that the market should provide the right financial incentives for the generation companies to invest in R&D. It is shown that what the right financial incentives are depends on factors such as the demand elasticity of the market, the cost of innovation and the cost effectiveness of the electricity produced by the new technology. Furthermore, it is argued that competition between generation companies for market share by providing cheaper electricity does not boost innovation per se. Innovating for cheaper electricity does not work in favor of generators, since gaining market share with lower prices does not balance the loss in revenue for the innovating generators, according to this model.

Interviews and reflections

Each of the analyzed cases implies different policy implications regarding particular potential strategic issues. In Chapter 8 of the thesis, the policy implications and insights gathered in each case are synthesized to reflect on the general course of liberalization in electricity sectors in relation to strategic behavior. Furthermore, the face validity and the actionability of the results are discussed in interviews with both academicians and industry practitioners. The proposed methodology in this thesis requires consultation with policy-makers and experts in the field. The aim of including the interviews was to provide some external validation for the use of formal modeling methodology, specifically game theoretical formal modeling, in analyzing the strategic relationships in liberalized electricity sectors. Additionally, the actionability of the results and the limitations of the models are discussed.

In conclusion

Game theoretical formal models are useful tools for assessing and debating strategic behavior. The models in this framework do not have the ambition of mimicing real-life behavior. Thus the aim of the modeling study is not to reach strongly decisive conclusions. Rather, the models aim to build insight into the modeled phenomena. Moreover, they have proven to be important means of communication for discussing and debating the underlying phenomena. In this regard, the models of this thesis serve as a discussion ground for strategic behavior. Furthermore, they offer various insights and reveal some potential areas of strategic behavior.

The thesis presents three cases about strategic behavior in liberalized electricity sectors. Although limited in scope and generic in their emphasis, the cases demonstrate the need for continued and ongoing analysis of strategic behavior in electricity sectors. I foresee that this dissertation can assist in the analysis of current mechanisms and inspire further mechanisms that can enhance the governance of electricity systems, both in Europe and around the world.

Samenvatting

De elektriciteitssector, net als vele andere infrastructuur systemen, wordt beschouwd als een onvervangbaar en een integraal deel van de economie van ontwikkelde landen. De economische groei, de levenskwaliteit en algemene welzijn van moderne samenlevingen zijn afhankelijk van een goed functionerend, betrouwbaar en efficiënt werkend elektriciteitssysteem. Lage niveau van betrouwbaarheid en efficiëntie kan risicos veroorzaken voor de industrie, de politiek en de samenleving. Al met al dient het onzichtbaar, betrouwbaar en efficiënt functioneren van het elektriciteitssysteem ieders voordeel. Hiervoor is een uitstekende management van het elektriciteitssysteem uitermate belangrijk.

Het management van de elektriciteitssector is in de afgelopen drie decennia door allerlei veranderingen gegaan. Tot in de jaren tachtig van de vorige eeuw werd de elektriciteitssector bestuurd door publieke en zakelijke monopolies. Deze monopolies behandelden alle soorten werkzaamheden van de waardeketen van de elektriciteitssector van het genereren en de transmissie tot de distributie, van de detailhandel tot de diensten. Van het kleinste operationeel niveau tot het strategisch besturen; alles werd binnen n verticaal geïntegreerd orgaan bewerkstelligd. Hierdoor kon er in geval van nood direct passend ingegrepen worden. Tevens was het mogelijk om het lange termijn plannen te optimaliseren; een raad van bestuur nam beslissingen over allerlei zaken zoals de opwekcapaciteit en uitbreiding van de transmissie capaciteit. Deze beslissingen waren gebaseerd op verscheidene data die werden gewonnen uit verschillende delen van waardeketen binnen dezelfde verticaal geïntegreerde organisatie.

Gedurende de jaren zeventig van de vorige eeuw begon de trend van het liberaliseren zich uit te breiden naar de elektriciteitssector, net als in de andere publieke sectoren, waaronder gas- en waterdiensten, telecommunicatie, lucht- en spoorwegtransport. Landen over de hele wereld hebben hun verticaal geïntegreerde elektriciteitsorganen sindsdien geliberaliseerd, met het doel om efficiëntere en vernieuwende markten te creëren uit de archaïsche elektriciteitssector. De nationale monopolies zijn veranderd in competitieve bedrijven vanwege bepaalde stappen van de liberalisatie, waaronder de ontbundeling, deregulering, privatisering en herregulering. Al deze stappen voor het creëren van competitieve elektriciteitssectoren hebben een grondige reorganisaties van het bestuur gevergd. Deze organisatorische veranderingen hebben naast de verwachte en nagestreefde voordelen ook vele problemen met zich meegebracht. Het strategisch gedrag van de marktdeelnemers is een van de keerzijden van de liberalisatie geworden.

Strategisch gedrag

OECD (1993) definieert 'strategisch gedrag' als volgt:

> "[H]et algemene begrip voor acties, welke zijn genomen door bedrijven voor het beïnvloeden van de marktomgeving waarin zij concurreren. Strategisch gedrag bevat onder andere acties voor het beïnvloeden van concurrenten om samen te werken voor het behalen van gemeenschappelijke winsten, als niet-coöperatieve acties voor het verhogen van de winsten van het bedrijf in het nadeel van de concurrent"

In dit onderzoek is dit begrip in een vergelijkbare betekenis gebruikt. Een bepaald gedrag is strategisch te noemen als dit gedaan wordt met de intentie om de marktomgeving te beïnvloeden voor eigen profijt. Hoewel het begrip in essentie niet negatief is, worden sommige specifieke strategische gedragingen in dit proefschrift aangegeven als nadelig. Niettegenstaande de moeilijkheid - soms onmogelijkheid- voor het bewijzen dat een bepaald strategisch gedrag nadelig is, kan de nadeligheid worden verondersteld in een nauwer verband, vooral in formele modellen waar de invloed van de actor gekwantificeerd kan worden.

Volgens de OECD definitie zijn er twee types strategisch gedrag: coöperatieve en niet-coöperatieve. In kapitalistische economieën is een vrije markt daadwerkelijk vrij zolang de bedrijven de competitieregels aanvaarden. Er zijn dusdoende verscheidene 'donts' die de bedrijven beperken. In een markt kunnen bedrijven niet samenzweren voor het vormen van een monopolie. De samenzwering van marktdeelnemers voor gemeenschappelijke voordelen ten koste van de marktvoordelen is een voorbeeld van coöperatief strategisch gedrag. Dergelijk coöperatief gedrag is echter niet de enige manier voor het manipuleren van de marktprijzen. Een voorbeeld voor niet- coöperatief strategisch gedrag voor het ophogen van prijzen binnen de elektriciteitsmarkt is het beperken van de elektriciteitsopwekking. Anderen voorbeelden zijn prijspredatie en het creëren van kunstmatige obstakels voor markttoetreding zijn andere voorbeelden. Al met al kan strategisch gedrag nadelig zijn vanuit het perspectief van zowel de maatschappelijk welvaart, als het welzijn van de markt. Dergelijk gedrag binnen de context van de elektriciteitsmarkt kan vertaald worden als hogere prijzen, minder vernieuwing en zelfs heftige black-outs.

Het geloof in het voorkomen van nadelig strategisch gedrag kan worden teruggevonden in de publieke en journalistieke opinie. Vanuit een juridisch en academisch perspectief is het echter in praktijk moeilijk oordelen of bepaald gedrag nadelig strategisch gedrag is. Dit komt voornamelijk door de bewijslast. De dunne lijn tussen strategisch gedrag en gepast competitief gedrag wordt getrokken op basis van de intenties van de bedrijven. Deze intenties worden echter zelfden openbaar gemaakt.

Het analyseren van strategisch gedrag binnen infrastructurele sectoren is niet een eenduidige zaak. Conventioneel gezien wordt marktconcentratie beschouwd als een indicatie voor marktmacht en is het daarom een bron voor strategisch gedrag. In een ideale markt wordt er gestreefd naar geen marktconcentratie en geen mogelijkheid voor manipulatie door bedrijven. De mededingen autoriteiten houden daarom toezicht op de marktconcentratie voor het opsporen van mogelijke misbruik van marktmacht. Gezien marktmacht niet meer de enige bron is voor strategisch gedrag, is het monitoren van de markconcentratie ook niet meer de enige methode voor het begrijpen en analyseren van strategisch gedrag. Het analyseren van strategisch gedrag moet gedaan worden met op maat gemaakte methodes welke rekening moeten houden met de details van het onderliggend systeem. In ons onderzoek is dit het elektriciteitssysteem. Deze studie hanteert een spel theoretische formele modelleerbenadering voor het analyseren van strategisch gedrag binnen de elektriciteitssector.

Doel en benadering van het onderzoek

De grootschalige veranderingen in de institutionele en regulerende organen van de elektriciteitssector brengen nieuwe belangen met zich mee, welke betrekking hebben op de interacties tussen nieuwe actoren. De nadelige strategische gedragingen van deze nieuwe actoren werden de belangrijkste zorg van de nieuwe elektriciteitsregimes naast de operationele en coördinatie gerelateerde zorgen. Ingewikkeldheden door de eigenaardige karakteristieken van de elektriciteitssectoren leveren een vruchtbaar grond voor het strategisch gedrag. De hoofddoelstelling van dit proefschrift is om een bijdrage te leveren aan het begrip van het potentieel strategisch gedrag in geliberaliseerde elektriciteitssectoren.

Er is geen kant-en-klare methode voor het analyseren van strategisch gedrag die in ieder situatie kan worden toegepast. Wanneer strategisch gedrag geanalyseerd wordt, moet er rekening worden gehouden met de karakteristieken van de sector. Een modelleerbenadering kan behulpzaam zijn voor het beschrijven van de eigenaardige karakteristieken van de elektriciteitssector met de marktdynamieken. Modellen die op maat gemaakt zijn voor specifieke sectoren of industrieën kunnen gebruikt worden voor het onthullen van potentiële strategische gedragingen. In dit onderzoek is een spel theoretische formele modelleeraanpak gekozen als de methode voor het analyseren van strategisch gedrag.

The research aims to answer the following main question:

> “Hoe kunnen we potentieel strategisch gedrag binnen geliberaliseerde elektriciteitssectoren begrijpen met behulp van spel theoretische formele modelering?”

Het onderzoeksterrein van deze studie is de geliberaliseerde elektriciteitssector. De Heilige Graal van het liberalisatieproces is het vormen van een totaal geliberaliseerde, zelfsturende en competitieve markt welke niet lastig gevallen wordt door het corrigerend ingrijpen van de overheid. De transitie van een nationaal monopolie naar een geliberaliseerde markt is een uitermate grootschalige en kostbare gebeurtenis. Het is uitermate moeilijk om te experimenteren met alternatieve vormen van beleid. Beleidsexperimenten zijn ofwel onuitvoerbaar ofwel te duur. Een alternatief voor experimenteren is formele wiskundige modelering en computationele simulering. Modelering en simulatie zijn een goedkope en veilig alternatief voor beleidsexperimenten. Daarnaast kunnen ze ook onverwachte inzichten in de problematiek opleveren. Vanwege de opkomst van nieuwe actoren en hun mogelijke strategische gedrag is speltheorie een passende modeleermethode. Immers, speltheorie kan gedefinieerd worden als de studie van de interacties tussen meerdere actoren.

Casussen: Gedachte-experimenten

De elektriciteitssector bestaat uit twee hoofdmarkten: de klein- en groothandel markten. In ieder van deze markten kunnen er gevari/ëerde vormen van strategisch gedrag voorkomen. In dit proefschrift wordt er gericht op beide markten en een potentieel strategisch gedrag in ieder van deze toegelicht. Daarnaast wordt er specifiek gekeken naar innovaties binnen de elektriciteitssector, omdat het gebrek aan innovatie van elektriciteitssectoren uit de pre-liberalisatie tijd als een pro-liberalisatie argument wordt gebruikt. Elk van de drie geanalyseerde casussen in dit proefschrift bevat een originele speltheoretische model voor het exploreren van het potentieel strategisch gedrag.

De tariefkortingen die de grootte/belasting van de elektrische stroom verschuiven (hierna *load-shifting price incentives* genoemd) in de elektriciteitsmarkten van de leverancier is het onderwerp van de eerste casus, welke in hoofdstuk 5 wordt geanalyseerd. In hoofdstuk 6 worden financiële transmissie rechten als een congestiemanagement methode geanalyseerd en er wordt daar bijbehorende mogelijke strategisch gedrag toegelicht. Het model van dit hoofdstuk bevat tevens een model van de elektriciteitsmarkt van de groothandel. Als laatst wordt er in hoofdstuk 7 de technologische innovatie in de elektriciteitssector bediscussieerd. Hierbij wordt er een speltheoretisch model van de innovatie binnen de opwektechnologie van elektriciteit gepresenteerd, welke helpt bij het trekken van conclusies met betrekking tot de relatie tussen competitie en technologische innovatie binnen de elektriciteitssector.

Casus 1: De *load-shifting price incentives* in de elektriciteitsmarkt van de leverancier

Het onderwerp van de eerste casus in dit proefschrift is de elektriciteitsmarkt van de leverancier. In het bijzonder is het door leverancier elektriciteitsbedrijven toegepaste mechanisme van *load-shifting price incentives* aan de consumenten geanalyseerd, waarbij hun vraag naar elektriciteit van de dag naar de nacht wordt verschoven. Een eenvoudige productieketen van de leverancier elektriciteitsmarkt is daarbij gemodelleerd. In dit model wordt de groothandelmarkt aangenomen als perfect geliberaliseerd, terwijl het aantal spelers in de leverancier worden beschouwd als een vrije variabele. Door het veranderen van de waarde van deze variabele, vergelijken wij het leverancier segment van de productieketen binnen een monopolie, oligopolie en perfecte markt situatie. Onze bevinding is dat in vergelijking tot binnen een monopolie de leveranciers binnen een perfecte leveranciermarkt minder mogelijkheden hebben tot het aanleveren van tariefkortingen (*price incentives*) aan klanten. Als een monopolie aanbieder opgesplitst wordt in meerdere onafhankelijke aanbieders, dan is de tariefkortingen van de onafhankelijke aanbieder lager. De onafhankelijke aanbieders kunnen zo kosten besparen en meeliften op de kortingen van de andere aanbieders. Er is dus sprake van een free rider ofwel 'meelift-gedrag'. De theoretische resultaten suggereren daarnaast ook dat de optimale individuele tariefkorting van elk van de aanbieders naar nul gaat als het aantal aanbieders toeneemt, gegeven dat klanten niet van aanbieder wisselen. Op basis hiervan suggereren wij dat tariefkortingen gereguleerd moeten worden.

Casus 2: Financiële transmissie rechten als een congestiemanagement mechanisme

Een ander geanalyseerde casus in dit proefschrift is een specifieke congestie management plan, namelijk de Financiële Transmissie Rechten (FTR). De FTR wordt besproken met betrekking tot diens strategische karakteristieken. In deze casus wordt er een speltheoretisch model van een gekoppeld FTR-elektriciteitsmarkt geformuleerd en er wordt een scenario geanalyseerd waarbij er kennis wordt achtergehouden als strategisch gedrag. Deze casus heeft twee hoofdcontributies. Ten eerste ontleedt het de fundamenten van de FTR en biedt levendige voorbeelden ervan. Het hoofdstuk licht samen met de FTR toe hoe de

Locationele Marginale Prijzen (LMP) zijn gecalculeerd en legt de LMP calculatie uit. Ten tweede demonstreert deze casus een situatie waarbij er potentieel strategisch gedrag wordt vertoond door de elektriciteitsproducenten. Deze scenario toont aan dat het opbouwen van opwekcapaciteit de waarde van FTR en sommige transmissielijnen binnen het netwerk verandert. Als een elektriciteitsproducent diens plannen voor de capaciteitsexpansie niet duidelijk openbaart, kan deze profijt halen uit deze privé gehouden informatie. Een maatregel tegen dit type gedrag is het houden van toezicht op mogelijke privé capaciteitswijzingsplannen van elektriciteitsproducenten binnen de FTR-markten.

Casus 3: Technologie innovatie in de electricititeitssector

De laatst geanalyseerde casus van dit onderzoek is gerelateerd aan de mogelijkheid tot innovatie binnen de sector van de elektriciteitsproducenten en is beschreven in hoofdstuk 7. Wij ondersteunen het idee dat ondanks liberalisatie er een gebrek is aan mogelijkheid tot innovatie binnen de elektriciteitssector. Het gebrek aan uitgaves aan Onderzoek & Ontwikkeling (O&O) leveren wij hierbij als bewijs. Wij willen duidelijk maken dat dit gebrek aan innovatie niet enkel afhangt van het gebrek aan competitie. Deze studie onderstreept bepaalde karakteristieken van het elektriciteitssysteem, zoals de inelastische vraag, als de remmers van innovatie. Er wordt een speltheoretisch model van de technologische innovatie in de productiemarkt aangeleverd, waar een simpel productieketen van de productiemarkt is gemodelleerd. Met dit onderzoek demonstreren wij dat de markt het recht op financiële beloningen moet verlenen aan elektriciteitsproducenten om te kunnen investeren in de O&O. Wij tonen aan dat het recht op financiële beloningen afhangt van factoren zoals de vraagelasticiteit van de markt, de innovatiekosten en de kosteneffectiviteit van de elektriciteit genereert nieuwe technologie. Daarenboven betogen wij dat een competitie tussen elektriciteitsproducenten, waarbij er middels aanleveren van goedkoper elektriciteit wordt getracht marktaandelen te winnen, niet per se tot innovatie hoeft te leiden. Volgens ons model is innovatie voor het aanleveren van goedkoper elektriciteit niet ten voordele van de elektriciteitsproducenten, gezien het inwinnen van marktaandelen met lagere prijzen niet de innovatiekosten van de generators balanceert.

Interviews en reflecties

Elk van de geanalyseerde casussen impliceren verschillende beleidsimplicaties met betrekking tot bepaalde potentiële strategieën. In hoofdstuk 8 van dit proefschrift worden de beleidsmatige implicaties en inzichten van ieder casus verzameld en samengebracht ter reflectie van de algemene koers van liberalisatie in de electriciteitssector met betrekking tot strategisch gedrag. Bovendien, de indruksvaliditeit en de actionability van de resultaten zijn besproken in de interviews met zowel academici als professionals binnen de industrie. De voorgestelde methodologie in dit proefschrift vereist consulten bij beleidsmakers en deskundigen van het veld. Het doel van het toevoegen van de interviews was om externe validiteit te kunnen leveren voor het gebruik van formele modelleringsmethode bij het analyseren van strategische relaties binnen de geliberaliseerde elektriciteitssectoren. Bovendien zijn de actionability van de resultaten en de limitaties van de modellen besproken.

Conclusie

Speltheoretische formele modellen zijn bruikbare middelen voor het beoordelen en bediscussiëren van strategisch gedrag. De modellen binnen dit raamwerk zijn niet gebruikt om het gedrag in het echte leven te simuleren. Het doel van het modelleren is dusdoende niet het bereiken van doorslaggevende conclusies. Het modelleren heeft echter tot doel om het verkrijgen van inzichten binnen de gemodelleerde fenomenen. Daarenboven hebben deze belangrijke toegevoegde waarde voor de communicatie van het bediscussiëren en debatteren van het onderliggend fenomeen. Met betrekking tot deze, de modellen van dit proefschrift dienen als een grond voor discussie van strategisch gedrag. Bovendien bieden zij verscheidene inzichten en onthullen bepaalde potentiële gebieden van strategisch gedrag.

Het proefschrift presenteert drie casussen over strategisch gedrag binnen de geliberaliseerde elektriciteitssectoren. Desondanks het gelimiteerde blikveld van de casussen demonstreren zij het belang van gecontinueerde en goeddraaiende analyses van strategisch gedrag binnen de elektriciteitssectoren. Ik voorzie dat deze dissertatie kan helpen bij het analyseren van huidige mechanismen en een inspiratie kan vormen voor verdere mechanismen die het regeren van elektriciteitssystemen kan verbeteren, zowel in Europa als over de hele wereld.

Dissemination

During the course of this research, there have been numerous occasions to publish and present the work in progress. Although some of the publication plan is still under way, some already achieved contributions are listed below.

First-authored peer-reviewed publications

- Oruç, S., Cunningham, S. W., 2014. Game-like characteristic of engineering design. In: Infranomics. Springer, pp. 257266.
- Oruç, S., Cunningham, S.W., 2013. Innovation in restructured electricity sector: Diagnosis, root causes, method of inquiry. In: Technology Management in the IT-Driven Services
- Oruç, S., Cunningham, S. W., 2012. Transmission rights to the electrical transmission grid in the post liberalization era. Journal of the Knowledge Economy, 120. (PICMET), 2013 Proceedings of PICMET13:. IEEE, pp. 26372648.
- Oruç, S., Cunningham, S. W., 2011. Strategic management of transmission access to the electricity grid. In: Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET11:. IEEE, pp. 16.
- Oruç, S., Pandharipande, A., Cunningham, S., 2010. An electricity market incentive game based on time-of-use tariff. International Stony Brook Conference on Game Theory.

Conference presentations

- *International Symposium for Next Generation Infrastructure, Vienna, Austria in 2014*
- *Technology Management in the IT-Driven Services (PICMET), San Jose, The United States in 2013*
- *International Energy Workshop, Paris, France in 2013*
- *Fourth Workshop on Game Theory in Energy, Resources and Environment, HEC Montreal, Canada in 2012*
- *Third International Engineering Systems Symposium (CESUN), Delft, The Netherlands in 2012*

- *Technology Management in the Energy Smart World (PICMET), Portland, The United States in 2011*
- 29th *International Conference of the System Dynamics Society, Washington, The United States in 2011*
- *SING 6 Game Theory Conference, Palermo, Italy in 2010*
- 25th *International Conference on Game Theory, Stony Brook University, New York, The United States in 2010*

Curriculum vitae

Sertaç Oruç was born on June 15, 1983 in Istanbul, Turkey. After receiving his high school diploma from Ankara Atatürk Anadolu Lisesi, he studied Electrical and Electronics Engineering at Middle East Technical University (METU) in Ankara. Upon receiving his BSc. degree from METU in 2006, he moved to the Netherlands to study Systems and Control at the faculty of Electrical Engineering at Eindhoven University of Technology. He successfully earned his MSc. degree from TU Eindhoven with his master's thesis on 'Scalable Distributed Kalman Filters' in 2008. After a short industrial experience as a Research Scientist at Philips Research Laboratories, in 2010, he began working on his PhD project at the faculty of Technology, Policy and Management at Delft University of Technology, under the supervision of prof.dr.ir. W.A.H. Thissen and dr.ir. S.W. Cunningham. The results of his PhD research are presented in this dissertation. As of April, 2014, he assumed a new role at the same faculty as Post-doctoral Researcher. His research interests include big data, data processing, data mining and visualization as well as game theory, electricity markets and strategic behavior.

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