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ELECTRICITY NETWORKS AND GENERATION MARKET POWER

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Some words of thank

While staying at the Center for several years, I already have seen several people finishing their PhD's. I must admit that every time I received one of these freshly printed dissertations, I almost couldn't wait until the soon-to-be-doctor would be out off sight, to quickly browse through the acknowledgements. I imagine that you, the reader, must be feeling something similar now.

It is a tradition in our working group to start the acknowledgments with a description of how we were hired by Stef Proost. Well, in my case, Stef offered me a job while I was visiting the bell tower of the Cathedral in Antwerp. Given that these bells make more noise than my phone I only found out one hour later what he had been trying to tell me. I never regretted working for Stef. He has always been full of energy, knew perfectly when I needed some motivation, and kept me perfectly on track. A lot of my intuition in economics I learned from him.

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1 Introduction

Many countries are currently liberalizing their electricity industries. To enhance competition, most countries separate the transmission sector from the generation sector. The transmission network not only transports electricity from where it is produced to where it is consumed, but also promotes market efficiency as it allows several generators to compete for the same consumers.

This dissertation discusses some topics on the liberalization of the electricity market. In particular, it looks at the allocation and the pricing of scarce transmission capacity and the regulation of the network operator in the presence of market power in the generation sector.

This introduction consists of four sections. The first section is a reader's guide. The second section briefly summarizes the technical aspects and the practical organization of the electricity market. The third section describes some of the problems associated with the network and with transmission.

The appendix gives an overview models that can be used to represent the different market structures of the electricity market. At the same time it discusses the models which are used in the thesis.

1.1 Guide to the reader

The thesis consists of three main parts:

Part I bundles three chapters which consider one dominant generator. It demonstrates that a more *efficient transmission market* will not always be beneficial. This is shown, both in a short term setting with a fixed transmission capacity (Chapter 2), and in the long term setting when investments in transmission are possible (Chapter 3). Chapter 4 studies different types of auctions for transmission rights. We investigate the degree of efficiency of the market for transmission rights.

Part II looks at a Cournot duopoly and discusses several ways to ration network access when there is congestion on a transmission line. The major result coming out of this analysis is that, when the network operator tries too hard to skim the congestion rents of the generators, there will be less competition in generation, no congestion on the network, and no revenue to be obtained by the network operator. Chapter 5 shows that the role of the network operator is crucial in creating competition among the generators, and in extracting congestion rent from the generators.

Part III studies the behavior of the network operator. It develops a computational model using data of the Belgian electricity market. Generators behave strategically and the high voltage network is represented by a Direct Current (DC) approximation which includes the (n-1)-security constraints (Chapter 6). Chapter 7 examines whether the network operator should always share all his information on the status of the network with the generators. It is shown that it may sometimes be better not to do this. Better information would allow a monopolistic generator to use his market power more efficiently, decreasing welfare.

Reading order

Section 2 of Chapter 1 gives a short introduction into the electricity market. Hence, this section is advised for readers who are not familiar with electricity. Chapter 2 and 3 are closely related. People unfamiliar with transmission constraints in the electricity market would probably prefer to read Chapter 3 first. Chapter 4 is a quite intuitive paper, and should help the reader to get some quick insights in the model. Chapter 5 can be read independently of the other parts as well. Chapter 6 uses the Generalized Nash Equilibrium of Chapter 2, but can be read independently as well. Chapter 7 stands separately from the other chapters.

Overview of the chapters

1. An introduction to the electricity market

PART I

2. Barring consumers from the network might increase welfare[1]

Extends the literature on the standard third degree price discrimination with limited arbitrage due to a limited transportation capacity. It shows that arbitrage is not always welfare improving.

3. Third degree price discrimination with costly arbitrage

[1]Presented in Berkeley (May 2003), Core (June 2003), Leuven (April 2002, April 2003) Electrabel (May 2003).

Long term version of Chapter 2. Extends the standard third degree price discrimination with costly arbitrage due to a transportation cost. It shows again that arbitrage is not always welfare improving.

4. Should an incumbent operator be allowed to buy importing capacity[2]

A two stage version of Chapter 2, with one of the markets competitive. It is shown that an importing monopolist values transmission rights more than local consumers. However, in a first price auction, he obtains no rights.

PART II

5. Modelling Cournot model in the electricity market[3]

Discusses several ways to ration transmission access when there is congestion. It shows a Nash implementation of the Generalized Nash equilibrium used by Oren (1997).

PART III

6. Regulating transmission in a spatial oligopoly: a numerical illustration for Belgium[4]

Compares some simple regulation mechanisms for the network operator, given that there is imperfect competition in the electricity market.

7. How much should the network operator tell?[5]

Shows that the network operator should withhold information, if information can be misused. He can only give credible information when he can commit to correct information revelation.

1.2 Description of electricity industry

This section explains the operation of the electricity industry. First, it describes the supply and demand characteristics of electrical energy. Then, the transmission of electrical energy is discussed. The third and fourth subsection describe the first best allocation and the potential market structures of the industry, respectively.

The aim of this section is to develop some feeling for the problems of the electricity industry. We take the view of an economist who would like to model the industry. The terms and notions that are used in the industry are defined differently in each country and depend a lot upon fashion. We will use as much as possible the definitions of the economics profession.

[2]Presented at the BAEE (March 2002), and ECN Netherlands (Sept 2003).

[3]Published in The Energy Journal (July 2002), Presented in seminars in Toulouse (January 2001), Bergen (August 2000), Leuven (June 2000)

[4]Joint work with Guido Pepermans. Presented in Leuven (September 2003)

[5]Presented at CORE (June 2003)

More information about the electricity sector can be found in the seminal work of Joskow and Schmalensee (1983) who discuss the operation of the electricity market in detail and show where there are economies of scale and scope. Bergen (1999) is a good handbook for the technical aspects of the network. Stoft (2002) wrote an interesting book aimed both at engineers and economists. It contains a lot of policy recommendations.

1.2.1 Four activities in electricity operation

Broadly speaking, four different activities can be found in the electricity industry: generation, transmission, distribution, and retailing.

1. *Generation* is the production of electricity by a mixture of mostly large power plants.

2. *Transmission* is the transport of electricity over the high voltage grid. Most generators as well as most large industrial consumers[6] are directly connected to this grid.

3. *Distribution* is the local, low voltage provision of electricity to small consumers.

4. *Retailing* is the billing, metering and marketing of electricity to small consumers.[7]

In this thesis I will focus on the first two activities of electricity provision: generation and transmission.

1.2.2 Properties of demand

Demand is characterized by a low short-run price elasticity. In the long-run electrical energy can be substituted by other energy forms, but the price elasticity remains small. Demand is highly variable during the year, but also during the day. Demand during peak hours can be double as high as during off peak hours. The highest demand during the year can be as high as three times the lowest demand.[8]

These demand properties drive the whole structure of the market. One of the main problems is how this fluctuating demand can be supplied.

[6] It is a typical Belgian situation that large industrial consumers are connected to the high voltage grid. In the Netherlands, the high voltage grid has no industrial consumers.

[7] Instead of retailing, one finds in the literature also the term *supply,*

[8] Note that demand is not only highly variable, but also stochastic.

1.2.3 Balancing generation and consumption

In general, equilibrium in consumption and generation can be obtained (Spulber, 1999) (1) by clearing the market through prices such that demand equals supply, (2) by rationing demand if the price is too low, (3) by suppliers who keep a stock in order to make sure there are no stock breaks.[9]

One option is thus to ration the consumers. But rationing of electricity is costly and not very selective. It is possible to shut down a complete region or a street, but it is impossible to reduce the supply to all consumers up to 90% of the demanded quantity. In the future new technological developments could make these adaptations easier.[10]

Market clearing is not workable either. If a consumer switches on a lamp, electrical energy should be provided immediately. This adaptation is automated and is faster than any market could clear.

Electrical energy is very costly to store, therefore demand for electricity should equal the production of electricity at every moment in time. In the electricity sector this equilibrium is obtained by generators who store energy in a different form than electrical: chemical, nuclear or mechanical energy and who have a conversion plant that can react fast enough to transform this energy in to electricity. In this respect, pumped storage plants play an important role in e.g. Belgium and Italy.[11]

The highly volatile demand and the non-storability of electricity require an optimal mix of generation plants, that can follow the fluctuating demand at least cost.

1.2.4 Properties of generation

Electricity is generated by production plants that differ in several aspects.

The first point of difference is their cost structure. Nuclear plants require large investment costs but have low marginal production costs. They are most profitable when they can run almost all the time. These plants (high investment costs, low marginal costs) are called base load plants. Other plants require only a small up front investment, but have high marginal costs. Investment in these plants is optimal when they are required to run a small number of hours during the year (these plants are called peak load plants.) Plants can be ranked according to the relative size of the investment costs and the marginal production costs.

[9] Producing electricity and then wasting what you do not need, is too costly.

[10] Sometimes 'rolling black outs' are used where each region is shut down for a certain period. Newer rationing systems make it possible to command centrally the operation of certain appliances as air-conditioning and heating.

[11] In fact, there are several energy reservoirs in a plant. For example in a classical thermal plant, the energy reservoir that reacts most quickly is the kinetic energy of the alternators who slow down when electricity demand increases. The second reservoir is the boiler which contains steam under pressure at a certain temperature. The third and largest reservoir is the chemical energy in the fuel used to fire the boiler.

Generation plants also differ according to the speed at which the production level can be adjusted and according to whether this change can be controlled. Nuclear plants can change the level of their output only in a small band around their nominal production level. When a cloud passes in the sky, the production by a photovoltaic installation changes rather quickly; but this happens not in a controllable way. New STAG plants can set their output over a whole range: from zero output to maximal capacity.

The time needed to start up a plant also depends upon its technology. For a coal plant, it can take up to eight hours until its boiler produces steam and can start to produce electricity. Such plants need to be scheduled at least one day before actual production. In most firms scheduling is even done for a whole week at once.

In most engineering literature, a generation plant is characterized by a minimal and a maximal production capacity. Between these two boundaries marginal production costs are fairly constant.

1.2.5 Transmission

This subsection gives a short description of the physics of the transmission network.[12]

Technical aspects

When electrical energy is transported over the network, the energy flows distribute themselves over the transmission lines according to the impedance of the transmission lines[13]. Their path can not be directed: when there are two parallel paths from point A to B the flows will take both routes.

Transmission networks carry Alternate Current (AC). The current changes direction 100 times a second. Also other variables fluctuate. In order to define a variable in such a system, two components are required: the maximal amplitude that the variable obtains, and the moment that it becomes zero.

The physics of the power flows[14] on the network are described by the power flow equations. These are two sets of non-linear equations: for each line that departs from a node there is a line equation, and for each node, one node equation.[15]

The line equation relates the voltage at the begin and the end node with the power flow that enters a line. This equation depends on the impedance of the transmission line.

The node equation states that the sum of the power flows leaving a node is equal to the sum of the power flows arriving in a node.

[12] It is a quite difficult task to explain all the aspects in a few lines. For more information look for example in Chapter 2 of Proost *et al.*(1999).

[13] The impedance is a physical property of a line which expresses how difficult a current flows through it.

[14] Power is the correct technical term for the amount of energy that is produced, consumed or transported in *a certain period of time*.

[15] To be correct, there are twice as much equations: one for each component.

Transporting electrical energy heats up the transmission lines, *i.e.* energy is lost during the transmission. Extra generation is thus needed to compensate these losses.

Several technical constraints limit the electricity that can be transported over the network. We will use only a subset of these constraints: the thermal constraints of the lines. Every line is considered to have an upper limit on the energy that can be transported, because otherwise the line temperature increase too much.[16]

Because flows cannot be directed, any transaction between two nodes will change the flows on all lines in the network. In order to 'translate' the line constraints in constraints on the consumption and generation quantities at the nodes, power flows have to be 'inverted'. After inversion one gets the set of feasible generation and consumption quantities that are possible given the characteristics of the network. This set is the production possibility set of the network operator. The production possibility set does not need to be concave, given that the power flow constraints are non-linear. The production possibility set can even be non-connected.

In the economic literature, the power flow equations are usually linearized, and network losses are assumed to be equal to zero.[17]

1.2.6 Security

The network operator makes sure that the network is operated securely. One of the dangers is that the failure of a single element causes the whole network to collapse. To prevent such a total collapse, it is imposed that the network should remain stable under all contingencies. This is captured by the so-called '(n-1)-rule', *i.e.* when a generator, a line, or a consumer breaks down, the network should remain safe.[18]

Each contingency defines a different state of the world. In terms of modelling, electricity is thus a 'highly differentiated' good. For each location, time period or state of the world, one has a different market, with a different clearing price.

However, from physically point of view, electrical energy is rather homogenous. For most applications, one kWh produced in one plant cannot be distinguished from the kWh of another plant. But even then electrical

[16]The heat loss warms up the transmission lines. The temperature of the line is limited by its mechanical strength, and the limit on the line sag. The thermal constraints are not strict: In winter, the lines have a higher capacity as they are cooled more easily. Also, for short time periods, higher flows can be accommodated, as it takes some time to heat up the line. See also Van Dommelen (1990).

[17]Such a linearized model assumes that the line resistance is small relative to the reactance, voltage magnitudes are the same at all nodes, and voltage angles between nodes at opposite ends of a transmission line are small. Engineers often use the linearized model of the network for long term planning.

[18]The n-1 is a static analysis of the security of the network. More realistic analysis requires dynamic assessments of the network during emergencies.

energy could be differentiated according to its power quality characteristics. Driesen *et. al.*, (2002) discuss the aspects of power quality in an economic setting.

1.3 Market organization

1.3.1 First best allocation

Define social welfare as the sum of gross consumers' surplus minus producer costs. The first best allocation is the set of production and consumption decisions that maximizes social welfare subject to the transmission constraints.[19] The solution of this problem has been established a long time ago by engineers, in what is called the optimal power flow problem (OPF-problem). See for example Wood and Wollenberg (1996).[20]

The dual variables of the constraints are the shadow prices. For each node they define a nodal price that induces players to choose the optimal production level themselves. This is called *nodal spot pricing* (Schweppe *et al.*, 1988).

In fact, under nodal spot pricing, transmission is priced at its opportunity cost. It ensures that, given the constraints of the network, generation and consumption are scheduled efficiently. This is called *short-run efficiency.*

The net transmission charge payed by the generators and consumers is the *congestion rent.*[21] This congestion rent can be used to reward investors who invest in transmission capacity. These congestion payments ensure that investment in generation occurs at the right location in the network. This is called *long-run efficiency.*

Optimal nodal pricing results in both short-run and long-run efficiency, giving the right signals for short-run production decisions and for investment in transmission and generation capacity.[22]

In practice, this remains largely theory. Transmission investments are

[19]The linearized transmission equations define a convex region. Under the usual assumptions (decreasing demand functions and convex generation functions) the objective function is concave in nodal injections. The optimization problem then has a unique solution. In reality cost functions of plants are not convex, (there are for example start-up costs, minimal production levels, *etc.*). Furthermore, the non-linear transmission equations do not lead to a convex region.

[20]Engineers mostly assume inelastic demand, and are mainly interested in cost minimization.

[21]Social welfare is divided in the net consumer surplus, the producers surplus and the revenue for the network operator.

In a network with transmission losses, the generators also have to pay for the transmission losses.

[22]These efficiency results assume decreasing returns to scale in generation, and investment in transmission capacity, and decreasing marginal utility of consumption.

Nodal spot pricing leads sometimes to counterintuitive results for economists, for some simple examples see Wu *et al.* (1996).

lumpy, co-ordination between generation and transmission investments are required, *etc*. Joskow and Tirole (2003) argue that private investment in transmission is probably not possible, even when the right property rights would be defined.

Implementation: two theoretical market structures

In a world with perfect information, the first best result can be implemented via a centralized system and as well via a decentralized system.[23]

- The *decentralized system* (Chao and Peck 1996, 1997). Electricity prices and transmission prices are determined as market equilibria. Two types of markets exist: one for electricity, where electricity prices are set, and another for transmission capacity, where transmission prices are set. Players act in both markets, and the network operator is responsible for the safety on the network and the creation of transmission rights.[24] Examples of decentralized markets are found in the Netherlands, PJM[25] and in California.

- The *centralized system*[26] (Bohn *et al.*, 1984 and Schweppe *et al.*, 1988). The network operator runs a large co-ordinated auction. Generators and consumers submit a supply respectively a demand function to the network operator. The latter then solves the welfare optimization problem, taking into account all constraints, by allocating consumption and generation quantities and setting nodal prices. Generators and consumers trade with the network operator and not directly with each other. Examples of centralized operation are the former England & Wales market, the National Australian market and the Nordic countries. The centralized model does not preclude the use of bilateral contracts. In most markets, players are allowed to write bilateral financial contracts (futures). These contracts are cleared upon the prices in the centralized market. In fact, these financial contracts mimic the decentralized contracts.[27]

[23] See also Boucher and Smeers (2001) for a description of the different market structures.

[24] There are basically two ways of defining transmission rights: link-based, and point-to-point. In the link-based system, users have to buy transmission rights for every congested line in the network, proportional to their impact on that line. In the point-to-point system, the transmission rights are already bundled in packages, and only one of these packages has to be bought. It would lead us to far to discuss the difference between the two systems.

[25] The PJM is a regional transmission organization (RTO) and coordinates the movement of electricity through all or parts of Delaware, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia and the District of Columbia.

[26] Sometimes the decentralized market system is also called the pool system, market splitting, or market coupling. See also Section 1.3.3.

[27] Both financial transmission contracts and financial electricity contracts can be created. See Hogan (1992) for a discussion of financial transmission rights in a centralized system.

1.3.2 Why no first best?

Several reasons exist why the first best cannot be achieved in practice. Two of them will be discussed here: strategic behavior and private information of the generators, and incomplete markets and contracts.

Imperfect competition is likely

Some observations suggest that generation is unlikely to be competitive. The number of players in the generation market is relatively small.[28] Transmission constraints hinder competition and create electrical islands, in which generators can have a local monopoly. Because generators produce different goods (peak and base load) generators do not compete with all generators in their island. Plants which operate on the margin are likely to set prices and to act strategically. Base load plants operate day in, day out. Most of the time they are price takers. So, at each moment in time there are only a limited number of players determining the prices. Players interact repeatedly with each other, which makes tacit collusion possible.

Competition is also hindered by asymmetric information. Generators have *private information* about their cost structure and the availability of their plants. It is not clear how uncertain this information is.[29]

Imperfect competition in the electricity market has been modelled in two different ways. Green and Newbery (1992) use the supply functions model of Klemperer and Meyer (1989) and show how the supply schedules are considerably above marginal costs. On the other hand, von der Fehr and Harbord (1993) develop a multi-unit auction where players submit a stepped supply function.

There is some empirical evidence of strategic behavior. Wolak and Patrick (2001) show how generators strategically withhold production capacity. Wolfram (1998) shows that in a uniform auction, multiple plant players have an incentive to bid higher for their marginal plants. However, the price cost margins are lower than predicted by theoretical models (Wolfram (1999)).

Imperfect competition and the interaction with the transmission network have been discussed by a number of authors. Joskow and Tirole (2000) compare the different market structures when one generator behaves strategically and other players are price takers. Other authors use Cournot models to study oligopolies. Oren (1997), Stoft (1999) and Willems (2002b) discuss

[28] In Europe, a number of mergers decreased this number even further, but at the same time the size of the markets increased as well.

[29] Cost differences in generation are primarily driven by the type of plant (coal plant, nuclear plant, *etc*). The plant type is observable, and cannot be considered private information. Cost differences between plants of the same type are relatively small.

The largest anecdotical evidence of asymmetric information deals with generators that reduce their production capacity during peak demand, declaring some of their plants unavailable for production. It is difficult to verify whether this is strategic behavior of the generator, or some *force majeur*, as a power plant is a complex machine.

the situation where generators are located on the same end of the line and compete to sell electricity to consumers at the other end of the line. Borenstein *et al.* (1998) study the opposite case where the generators are located at different ends of the transmission line. Given the Cournot assumption these papers do not explain very well how transmission prices and electricity prices are set. As an alternative, Smeers and Wei (1997) assume that transmission is priced at the opportunity costs of the generators.

The number of property rights is so large that incomplete contracts are likely

A decentralized market would require property rights for every transmission line in the network, for every moment in time and for every possible contingency. The number of property rights would rapidly become immense.

Given the large number of goods, transaction costs play an important role in defining the optimal market structure. There will probably not be a full set of markets; and contracts are likely to be incomplete.

Even if markets would be complete an efficient equilibrium would not be obtained easily. A generator who sells electricity to a consumer needs to sign an electricity contract with this consumer. Furthermore, he needs to buy transmission rights for each line in the network, proportional to the influence of his transaction on this line. If he misses one of these rights, transport is impossible. Property rights are thus close complements. Sequentially auctioning complementary goods is not efficient. Instead, some form of coordinated auction is needed.[30] For an survey of the problems in defining property rights see Hogan (2000).

What is Second Best?

Under imperfect competition, the centralized and the decentralized system do no longer yield the same result. Much has been said about which system would be best. However, no consensus has been achieved yet.[31]

Most people do agree that shortly before actual production (some hours before operation), the market should be coordinated and organized centrally.[32] In the long-run, bilateral contracts could be more useful than centralized contracts.[33]

[30] If several network constraints are binding, efficiency requires multi-lateral trading instead of bilateral trading.

[31] Some of these discussions are collected on the following websites: http://www.stoft.com and http://www.ksg.harvard.edu/hepg/.

[32] Chao *et al.* (2000), supporters of the centralized system, proposed recently a hybrid form, a centralized short term market and a bilateral long term market.

[33] Long term contracts reduce the associated risk with new investments in generation and transmission capacity. But it is not completely clear why centralized contracts would be worse than bilateral contracts to achieve this.

1.3.3 Practical implementation

Functional unbundling

In the past, the electricity sector was organized in vertically integrated firms. These firms were responsible for all four functions: generation, transmission, distribution, and retailing. They internalized all consequences when taking investment and operation decisions. Most of these firms received regional exclusivity for the provision of electricity. Prices and major investments were regulated by a regulator.

Recently, competition has been introduced for some of these activities. Since economies of scale in transmission and distribution services are large, they are considered to be natural monopolies.[34] Therefore, they are operated by a network operator which is regulated.[35,36] The production of electricity, and in some countries retailing, is assumed to be open for competition. This splitting of functions is called functional unbundling. In Europe this process has been catalyzed by the European directive on the electricity markets. For a discussion of the deregulation in the United States and Europe see Joskow (2000) and Van Roy *et al.* (2000), respectively.

Transmission markets

In theory, the transmission prices should be different in each node in the network. In practice, nodes are aggregated into zones. Intra-zonal transmission is not priced, while inter-zonal transmission is priced.

Transmission within a zone is basically free. If there happens to be congestion within a zone, then the network operator has to solve congestion by signing transactions with consumers and/or generators to counter-act it. The associated costs are socialized and paid by all users. Harvey and Hogan (2000) reports that this can lead to gaming by the generators.

For transmission from one zone to another, one of the standard models is used: the centralized market structure or the decentralized market structure.[37] In the decentralized market, transmission rights for cross border trade are auctioned. In the centralized market[38] transmission is allocated implicitly.

[34] Nevertheless, some U.S. cities have two competing distribution networks.

[35] The precise activities of the network operator can differ. They always include the security and real time operation of the network. Mostly the network operator organizes some markets (see later).

[36] Germany is one of the few exceptions, transmission prices are negotiated between the different generators. The anti-trust authorities have to judge if there is no abuse of market power. From July 2004 on, a dedicated regulator will be appointed.

[37] The centralized and the decentralized allocation of transmission rights are market conform allocations.

At the Belgian-France border, access to transmission capacity is rationed. This is a non-market conform mechanism.

[38] In this setting the centralized market is also often called the market splitting method.

The problem of auctioning transmission rights is that it is impossible to define such transmission rights in a meshed network (Boucher and Smeers, 2002).[39]

The market splitting method is more elegant, but requires that both zones have co-ordinated energy markets.[40]

Different Energy markets

Because a real time spot market cannot be organized in practice, the network operator can operate several types of markets: a day ahead market, a balancing market, reserves markets and futures markets. These markets differ with respect to the time frame in which they operate. Some of these markets can also be organized bilaterally or by independent exchange.

The *day ahead market* comes closest to a real time market. In fact, it is a forward market on which prices are set a day before actual delivery of electricity.[41] Generators (consumers) agree to produce (consume) the next day a certain amount of electricity at a certain fixed price. The day ahead market is cleared physically by the production (consumption) of electricity.

The network operator uses the *balancing market* to adjust in real time small imbalances between demand and supply. Only some generation plants can adjust their quantities fluently enough to provide this service.

Next to the balancing market the network operator operates several *reserve markets*. These reserve markets are differentiated according to the speed at which these generators can change their production level or start up their plants.

The last two types of markets (reserve markets and balancing market) are actually option markets, *i.e.* the generators sell the network operator the right to call their plants in service.

These three types of markets can be extended with several *future markets* (typically from one day to three years before delivery). Most of these long term future contracts are cleared financially upon the price that is established in the day ahead market. Generators and consumers agree for instance in 2003 on an electricity price for year 2004. If the actual price on the day-ahead market is above the price agreed upon, the generators will pay the difference to the consumers. If the actual price is lower, the consumers refund the generators.[42]

Some market organizations have been afraid that not enough generation

[39] There are several problems. One of the main problems is that not every transaction between the two countries has the same impact on the interconnecting transmission lines.

[40] Also in the decentralized market, co-ordination of the energy markets could be beneficial. On the German-Dutch border, the market for transmission clears first, then the German energy markets, and finally the Amsterdam power exchange.

[41] In some markets, the day ahead market is called the spot market.

[42] In Belgium a day ahead market does not exist, therefore all long term contracts are cleared physically.

capacity would be build. Given the recent black-outs, this might be exactly what is happening.

In order to have sufficient investment in generation, generators are paid for owning a plant, even if it is not generating (availability payment). It is not clear whether these payments have an economic justification.

If the spot and the reserve markets are working well, theory predicts that sufficient investments will be made by competitive generators. The basic problem with the capacity payments is that they often do not require the generator to generate electricity at a certain price. They are thus a call option where the strike price can be set by the seller. Such an option has no value.[43]

Appendix 1.A Modelling market structures

The aim of this section is to describe the models used in this dissertation to model imperfect competition in a network with transmission constraints. We show which type of model is appropriate for which market structure. Besides that we also look under which assumptions different market structures give the same market outcome, *i.e.* when they are *equivalent.*

This section is rather condensed and refers to models and results that are derived more extensively in later chapters of the thesis.

1.A.1 Different market structures

As noted before, the electricity sector can be organized according to three different market structures: integrated, centralized, and decentralized. Table 1.1 gives an overview of the different structures.

We look at three activities in the wholesale electricity market:

1. electricity generation
2. physical electricity transmission
3. electricity sales

With "sales" we also indicate the *intermediation* between consumers and generators, and the regional price *arbitrage.* The definition here is thus not exactly the same as we used before.

Before the liberalization of the electricity sector, one regulated firm would preform these three activities: they were thus all integrated in one firm. We call this the *integrated market structure.*

With liberalization, the generation and the transmission function were separated from each other. In the European legal terminology this is called

[43]Cramton (1999) gives some economic considerations for one particular market structure in New England.

MARKET STRUCTURE		FUNCTION		
Name	*Description*	*Gen.*	*Sales*	*Trans.*
Integrated	One firm decides about *generation*, *sales*, and *transmission*	R	R	R
Centralized	Generators compete for production, *production* Network operator set *sales*, *transmission*	M	R	R
Decentralized	Generators set *production* and *sales* Network operator creates *transmission rights* Market sets *transmission*	M	M	R

Gen.*: generation,* ***Trans.****: transmission* ***Sales****: Sales, Intermediation, Arbitrage*
R*: one (regulated) firm;* ***M****: market, mostly several firms*

Table 1.1: The three main market structures

unbundling, as opposed to *integration.* As was explained in 1.3.1, two market structures can be developed: the centralized and the decentralized market. The two structures differ in how they organize the third function in the network: sales, arbitrage and intermediation.

In the *centralized market structure*, generators and consumers submit bids to the network operator to produce or consume electrical energy. The network operator solves an optimization problem taking into account the network constraints. He sets production and consumption quantities and clears the markets. In this system transmission is allocated implicitly by the network operator. Generators are only responsible for their generation. The network operator is a sort of intermediator, an arbitrageur between the different generators and consumers.[44]

In the *decentralized market structure,* the network operator creates transmission rights. Generators decide about their production levels, buy transmission rights and set their sales in each region. Transmission prices are set on the market for transmission rights. Arbitrageurs will buy electricity in one region, and after paying for transmission rights, they will sell it in another region. The difference with the centralized market is that the generators cannot only set their level of production, but also their level of sales.[45]

Intermediation between consumers and generators and arbitrage between regional price differences is no longer the monopoly of the network operator.

The colored cells in Table 1.1 are the functions for which only one firm is responsible. For the other cells several firms can compete to provide the service.

The decentralized market can be modelled in several ways, depending on the way the transmission markets are organized: (Table 1.2.)

[44] In the centralized market organization, transmission and intermediation are kept mostly the same firm, or in two, closely co-orporating institutions.

[45] We make abstraction of losses on the network. Mostly the network operator will need to buy electricity to cover the losses on the network.

Assumption	*Description*
One stage	The markets for transmission and for energy clear at the same moment.
Two stages	The market for transmission clears first, then the market for energy.
No Arbitrage	There are no arbitrageurs; the transmission price is not equal to the regional price difference.
Perfect arbitrage	The transmission price is equal to the regional price difference.
Withholding	A transmission right gives the right but not the obligation to transport electricity
No-withholding	A transmission right gives the right and the obligation to transport electricity

Table 1.2: Options to model the decentralized market

- *One stage* versus *two stage* models
  In a one stage game, the transmission market and the market for electricity clear at the same moment. In the two stage game, first the market for transmission clears, then the market for electricity. The difference in timing has an effect on the strategic behavior of the players.

- *arbitrage* versus *no arbitrage*
  With perfect arbitrage, the price regional price difference is equal to the transmission price. Without arbitrage, the transmission price and the price difference are unrelated.

- *Withholding* versus *no withholding* of transmission rights.
  If withholding of transmission capacity is allowed, the generators can buy transmission rights and decide not to use it. If withholding is not allowed, the generators are obliged to use all the transmission rights that they own.

1.A.2 Equivalence of market structures

The thesis assumes that withholding by the generators is not allowed.[46] For the decentralized market, 2 * 2 different market models remain. Together with the centralized market and the integrated market there are six different models (Table 1.3). Appendix 1.B gives a formal description of these models in a simple monopolistic setting.

[46] In practice withholding cannot be forbidden completely, as it is always possible that a generator has an unexpected problem with a generation plant. It is assumed that the punishment for withholding is high enough to rule out any strategic behavior by the generators.

ARBITRAGE MODELS		equivalent with *centralized*, if:
1	*centralized*	-
2	*decentralized, one stage, arbitrage*	always
3	*decentralized, two stage, arbitrage*	one generator
NO ARBITRAGE MODELS		equivalent with *integrated*, if:
4	*integrated*[1]	-
5	*decentralized, one stage, no arbitrage*	one generator perf. elastic supply of transmission
6	*decentralized, two stage, no arbitrage*	one generator perf. elastic supply of transmission

(1): unregulated

Table 1.3: Equivalence results.

If we look at the market outcome, these six market structures can be grouped in two categories: one category called 'arbitrage' and another category called 'no arbitrage'.

The models within a category are equivalent as long as certain conditions are met. We will now discuss these conditions.

The most robust result is the equivalence of (#1) the centralized model and (#2) the decentralized model with perfect arbitrage in a one stage model. (The number refers to the line in Table 1.3) This result is valid for a broad range of models. (Boucher and Smeers, 2001; Metzler *et al.*, 2003; Day *et al.*, 2002) It means that it does not matter whether generators only set their production level at each generation plant, or whether they set their production level and the level of their sales in each region. The regional sales of the players do not have to be equal in both market structures, but profit, total sales, and all prices, are equal under both market structures. (The intuition behind the equivalence result is shown for the monopoly case in appendix 1.B).

The second equivalence extends the first: in a monopoly game, (#3) the two stage decentralized market with perfect arbitrage and (#1) the centralized market are equivalent. (For the proof see the appendix of Chapter 4.) In an oligopoly setting this result is no longer valid: Neuhoff (2003) shows that (#1) the centralized market is more competitive than (#3) the two stage decentralized market with perfect arbitrage.

The third result is the equivalence between (#5) the decentralized one stage model without arbitrage and (#4) the integrated model. The monopoly assumption is needed because the integrated model has by definition only one generator. The perfect elasticity assumption is needed because otherwise the monopolist will behave as a monopsonist in the transmission market if he does not own transmission.

The fourth result is the equivalence of (#6) the decentralized two stage model without arbitrage and (#4) the integrated model. If there is only one player, it does not matter whether the model has one or two stages, as there are no strategic interactions between the players.

Assumption	*Description*	*Arbitrage?*
First Price Auction	Each player pays the marginal bid (= the clearing price)	$\Delta p = \tau$
Pay-as-bid Auction	Each player has to pay the bid that he submitted.	$\Delta p > \tau$

Table 1.4: Market micro structure and arbitrage.

Models in this dissertation

Chapter 2, 3 and 4 consider a single dominant generator in a network with only one transmission line.

Chapter 2 compares (#2) the decentralized one stage model with arbitrage and (#5) the decentralized one stage model without arbitrage. It is shown that arbitrage is not always welfare improving.

Even if arbitrage is bad in the short-run, when transmission capacities are low, it is possible that arbitrage is optimal in the long-run: it gives private investors an incentive to extend the transmission capacity. This is studied in Chapter 3.

Chapter 3 is the long term version of Chapter 2. In the long-run, transmission capacity is no longer fixed: new investments will be made in transmission capacity. With arbitrage, private investors will invest in transmission lines as long as the price difference between two regions is larger than the cost of transmission expansion. The monopolist will act, taking into account the behavior of the investors in transmission lines. Without arbitrage, the monopolist himself decides about the amount of transmission lines built.

Chapter 4 models (#3) the two stage decentralized market with arbitrage. In stage one, the monopolist buys transmission rights. In stage two, he sets the price for electricity. The incentives for the monopolist are explained.

Chapter 4 then looks at two different market micro-structures for allocating the transmission rights in the first stage: the first price auction and the pay-as-bid auction. With the first price auction, arbitrage is perfect (Table 1.4).[47] With the pay-as-bid auction, arbitrage is not perfect. The price for transmission is smaller than the price difference.

The appendix of Chapter 4 shows that the (#3) two-stage decentralized market with perfect arbitrage is equivalent with a (#2) one-stage model with perfect arbitrage.

1.A.3 Modelling problems

In the models with perfect arbitrage (#1-#3), the transmission price does not change smoothly as a function of the output of the generators. The generators take this constraint into account when they maximize profit. They have to

[47] This result was only proven under the assumptions in the model (monopolist, small transmission capacity), but might be valid in more general circumstances.

N°	Type of model	Transmission price	Nash Equilibrium?
1	Generalized Nash Equilibrium *(Harker, Oren)*	No transmission price	No
2	Price taking in transmission *(Smeers & Wei)*	Price that clears market	No
3	All or nothing rationing	No transmission price (OR: taxing all rents)	Yes
4	Proportional rationing	No transmission price	Yes
5	Efficient rationing	Taxing rent of high cost producer	Yes

Table 1.5: Generalized Nash equilibrium, and some variants

solve a mathematical programs with equilibrium constraints (MPEC). MPEC can have several local optima, as can be seen in Chapters 1 and 2.

If we extend the model to a game with several players, a Nash equilibrium does not always exist. Larger problems, with multiple generators and multiple transmission lines, cannot be solved very easily with those models. Nevertheless, Hogan (1997), Borenstein *et al.* (1998) and Hobbs, Metzler and Pang (2000) solve some of these games.

The models without arbitrage (#4-#6) cannot be modelled as Cournot-Nash games. If each generator can independently set his production level, it is not guaranteed that the transmission constraints will not be violated. One would need a rationing rule to define what happens in such a case.

The next subsection discusses a simplification of the models which allows numerical simulations and some rationing rules.

1.A.4 Simplifying assumptions

Most numerical models assume that generators are *price takers in the transmission market*, and Cournot competitors in the market for energy.

This approach has been taken by Smeers and Wei (1997). It is numerically very elegant, and can be solved for a large network, with multiple players. Using this simplification, the same market structures as in the previous subsection can be studied. (Appendix 1.C shows the implementation for the network with one transmission line.)

It can be shown that the equilibrium production quantities of the Rawlsian model are also a Generalized Nash Equilibrium (GNE) (Harker, 1991).[48] In a GNE generators jointly face the transmission constraint. They coordinate implicitly, so that there will never be congestion. There are typically a large number of GNE, from which the equilibrium of Smeers and Wei is one. Neither the GNE, nor the equilibrium of the Rawlsian model are a Nash equilibrium (See the first two lines in Table 1.5).

[48] In a GNE, the transmission price is zero, in the Rawlsian model, transmission prices clear the market for transmission.

Models in this dissertation

Chapter 5 looks at a simple Cournot model where two generators are located at one end of a transmission line and consumers at the other end. Transport over the line is costless, but there is a transmission constraint.

The model looks at (#1) the centralized system. However, as there are only consumers on one end of the line, this is basically a model where arbitrage cannot play a role. The model can thus also be seen as (#5) the decentralized one stage model without arbitrage. Oren (1997) studies this problem using the GNE of the Cournot game.

Chapter 5 looks for three Nash equilibria of this game. In order to do so, the role of the network operator is made explicit. The network operator uses a rationing rule. Three rationing rules are studied: *all-or-nothing, proportionality,* and *efficient rationing*. (See the last three lines in Table 1.5).

With the *all-or-nothing rationing* rule, the network operator forbids access to the transmission line when demand for transmission is higher than the capacity. It is shown that this equilibrium is the same as the GNE of Oren. The first three lines of Table 1.5 are thus closely related.[49]

With the *proportional rationing* rule, the network operator allocates capacity *proportionally to the bids* if there is congestion.

With *efficient rationing*, the entire rent of the least efficient generator is taxed if there is congestion, whereas transmission is not taxed if there is no congestion.

Chapter 6 uses the Rawlsian model and models the strategic behavior of the network operator in a congested network with imperfect generation. It uses a two stage Stackelberg game. First the network operator sets transmission prices, then the generators set production and sales. Several scenarios for the generation market structure and the behavior of the network operator are compared.

Appendix 1.B Illustration: market structure models

1.B.1 Set up of the model

This section illustrates the implementation of the different market structures in a simple model. It considers a monopolistic generator and a one line network. The model is presented in Figure 1.1.

There are two regions $i \in \{1, 2\}$. In region i, the monopolist sells s_i units of electricity at a price p_i and generates q_i units at a constant marginal cost

[49] Another interpretation of the all-or-nothing rule, is that the network operator taxes all the rent of both generators as soon as there is congestion. The generators make zero profit when they create congestion, and hence avoid doing so. As a result, the network operator receives no congestion payments. This was already claimed by Oren.

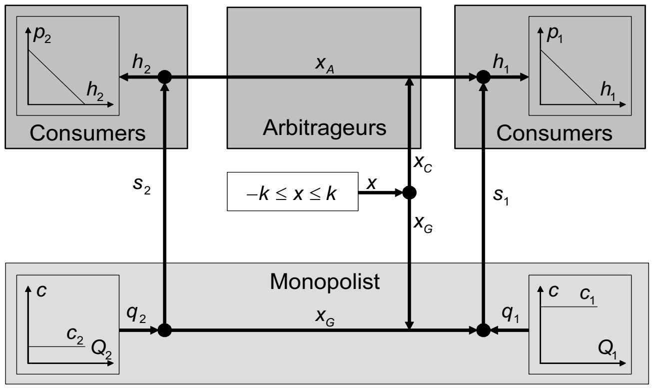

Figure 1.1: The two region model with monopolist production.

c_i. The monopolist transports x_G units from region 1 to region 2. (If x_G becomes negative, then he transports in the opposite direction.) A price τ is paid for transport.

The profit of the monopolist is equal to sales minus production and transport costs.

$$\pi = p_1 s_1 + p_2 s_2 - c_1 q_1 - c_2 q_2 - \tau x_G \tag{1.1}$$

The generator can only sell in a region what he produces and imports in that region.

$$q_1 = s_1 - x_G \tag{1.2}$$
$$q_2 = s_2 + x_G \tag{1.3}$$

If there are arbitrageurs, then they will arbitrage on the price difference between the two countries. They buy x_A units of electricity in region 2 at a price p_2 and sell it in region 1 for a price p_1. They pay a price τ to transport the good from region 2 to region 1. Arbitrageurs cannot make a profit. Therefore in equilibrium we must have

$$\tau = \Delta p \tag{1.4}$$

with $\Delta p = p_1 - p_2$. Equation 1.4 is the arbitrage constraint. If there are no arbitrageurs, then the price difference does not need to be equal to the transportation cost.

Consumers have a demand function $h_i(p_i)$. In region 1, the consumers buy x_A units from the arbitrageurs and s_1 units from the monopolist. In region 2, they buy s_2 units from the monopolist, but resell x_A units to the arbitrageurs.

$$s_1 = h_1(p_1) - x_A \tag{1.5}$$
$$s_2 = h_2(p_2) + x_A \tag{1.6}$$

The total demand for transportation is the sum of the demand by the monopolist and the arbitrageurs $x = x_A + x_G$.

The two regions are connected by a transmission line with capacity k. Transmission is costless, but total transmission x should be smaller than the available transmission capacity

$$-k \leq x \leq k \tag{1.7}$$

A network operator selling x rights for a price τ will make a profit $\tau \cdot x$. If he is a price taker, he takes the transmission price as given, and maximizes his profit subject to the transmission constraint.

$$\max_x \tau x \tag{1.8}$$

$$\text{s.t. } -k \leq x \leq k \tag{1.9}$$

This gives us the supply function of transmission capacity. As long as $\tau > 0$, he sells k transmission rights. If $\tau = 0$, he is indifferent with respect to the number of rights that he sells $-k \leq x \leq k$. If $\tau < 0$, he sell k transmission rights in the opposite direction. The behavior of the network operator is described by his supply 'function' $\tau(x)$:

$$\tau = 0 \Rightarrow -k \leq x \leq k \tag{1.10}$$

$$\tau > 0 \Rightarrow x = k \tag{1.11}$$

$$\tau < 0 \Rightarrow x = -k \tag{1.12}$$

1.B.2 Different market structures

Substituting the energy balances 1.2, 1.3, 1.5 and 1.6 in the profit function of the monopolist we obtain:

$$\pi = h_1(p_1)(p_1 - c_1) + h_2(p_2)(p_2 - c_2) + x\Delta c - x_A \Delta p - x_G \tau \tag{1.13}$$

with $\Delta p = p_1 - p_2$, $\Delta c = c_1 - c_2$.

It is instructive to analyze the different terms of the objective function:

- The first two terms is the local profit the monopolist makes if all electricity is produced locally and consumed locally.
- The third term is the gain in production efficiency, as x units of electricity are produced in country 2 instead of country 1.
- The fourth term is the loss of sales, to consumers who do not buy all electricity locally but buy some electricity from the arbitrageurs.
- The fifth term is the cost of buying transmission capacity.

Integrated		Centralized	
$-k \le x \le k$ $\tau = 0$ $x_A = 0$	$h_i(p_i) \ge 0$ $q_i \ge 0$	$\Delta p = \tau(x)$ $x_G = 0$	$h_i(p_i) \ge 0$ $q_i \ge 0$
Decentralized - No Arbitrage		**Decentralized – Arbitrage**	
$\tau = \tau(x)$ $x_A = 0$	$h_i(p_i) \ge 0$ $q_i \ge 0$	$\tau = \tau(x)$ $\tau = \Delta p$	$h_i(p_i) \ge 0$ $q_i \ge 0$

Table 1.6: Constraints in the optimization problem

The monopolist maximizes his profit function, subject to some constraints. Those constraints depend on the market structure. For each type of market structure the constraints are shown in the Table 1.6.

In all cases the level of consumption and generation should be positive

$$h_i(p_i) \geq 0 \tag{1.14}$$
$$q_i \geq 0 \tag{1.15}$$

In the *integrated market*, the monopolist owns transmission capacity. He does not need to pay for it, $\tau = 0$, there are no arbitrageurs, $x_A = 0$, but there is still the transmission constraint.

In the *centralized market*, the monopolist is not allowed to transport over the network $x_G = 0$, and can only sell at the region of production. The network operator will arbitrage on the price differences. As long as transmission capacity is available, the price difference is zero $\Delta p = 0$. If there is congestion, the price difference can become positive; $x = k$ and $\Delta p > 0$. The behavior of the network operator is thus as $\Delta p = \tau(x)$.

In the *decentralized market* the network operator sells transmission capacity at a price $\tau = \tau(x)$. If there are arbitrageurs, the price difference is equal to the price of the transmission rights: $\Delta p = \tau$. Without arbitrageurs the quantity transported it equal to zero $x_A = 0$.

Equivalence results:

The integrated market and the decentralized market without arbitrage are equivalent. At first sight, the monopolist would prefer the integrated market structure to the decentralized market without arbitrage, as the transmission price τ is always zero. However, the monopolist can obtain the same profit under decentralized market structure without arbitrage by transporting an amount of electricity equal to $k - \varepsilon$.

The centralized market and the decentralized market with perfect arbitrage are equivalent as well. In the centralized market the monopolist faces an additional constraint: he is not allowed to transport electricity. However, given perfect arbitrage the monopolist is indifferent whether he transports electricity or whether arbitrageurs transport electricity.

For the proof, substitute the arbitrage constraint $\Delta p = \tau$ in the objective function 1.13. The profit function then depends only upon x, and not on

Description of model	Generator chooses:	Subject to:	Assuming Fixed:	Equilibrium conditions
Centralized	p_i, x_G, x_A	$x_G = 0$ $\Delta p = \tau$	τ	$\tau = \tau(x)$
Decentralized, External arbitrage	p_i, x_G		τ, x_A	$\Delta p = \tau$ $\tau = \tau(x)$
Decentralized, Internal arbitrage	p_i, x_G, x_A	$\Delta p = \tau$	τ	$\tau = \tau(x)$
Decentralized, No Arbitrage	p_i, x_G		τ, x_A	$\tau = \tau(x)$ $x_A = 0$
Decentralized, No arbitrage	p_i, x_G, x_A	$x_A = 0$	τ	$\tau = \tau(x)$

Table 1.7: Models with price taking in transmission market

x_G or x_A separately. It can be shown that the constraints also depend only upon x, and not on each of the components x_G or x_A.

Appendix 1.C Illustration: Simplified market structure models

The problems of the models in the previous appendix is that (1) the objective function is not concave due to the term $(\tau \cdot x_G)$ and that (2) the constraint $\tau = \tau(x)$ is not a convex constraint. As a result, generators have to solve a mathematical program with equilibrium constraints (MPEC). These models are hard to solve.

A simplification of the model is to assume that the monopolist is a price taker in the transmission market, and takes τ fixed. On the electricity generation market he remains a strategic player.

Several market structures can again be implemented. Each line in Table 1.7 describes a different model. The second column describes the variables that are set by the monopolist. The third column are the constraints that are faced by the monopolist. The fourth column are the variables that are assumed to be fixed by the monopolist. The fifth column gives the equilibrium constraints that are external to the firm, but that determine the variables in the fourth column.

In fact, all these formulations lead to only two different outcomes: a market with perfect arbitrage, and one where arbitrage is not perfect. The first three models in Table 1.7 are equivalent. Also the last two models are equivalent.[50]

[50]The centralized system gives different regional sales for the generator, but that is just an accounting difference.

Part I

Monopolistic Generation and Arbitrage

2

Barring consumers from the electricity network might improve welfare

This paper extends the standard model of regional price discrimination, and applies it to the electricity market. To the standard model, it adds limited transport capacities, and regional production cost differences. It is shown that the intuition changes in the extended model.

2.1 Introduction

The paper starts from the classical industrial organization model of regional price discrimination [1]: A monopolist sells a homogenous good in two regions. If there is no regional arbitrage – *i.e.* the two markets are perfectly sealed[2]– the monopolist can set a different price in each region. If there is regional arbitrage, the monopolist can only set a uniform price for both regions.

The welfare effect of arbitrage is ambiguous. Varian (1985) shows that two effects play a role:

The efficient allocation of an amount of goods over consumers in two regions requires that the consumers have the same marginal willingness to pay across the regions. Arbitrage guarantees the efficient allocational of goods. If arbitrage would not have an impact on the number of goods produced by the monopolist, it would clearly increase welfare. We will call this direct effect the *allocational effect.*

However, the monopolist will adjust its output as a reaction to arbitrage. He will contract or expand production, depending on the shape of the de-

[1]This is the so called the third degree price-discrimination.

[2]The term 'sealing' originates from Wright (1993).

mand functions. A production increase has a positive impact on welfare. A contraction has a negative impact. This indirect effect of arbitrage will be called the *output effect*.

Total effect on welfare is the sum of both effects: arbitrage increases allocational efficiency, but might induce a strategic response of the monopolist, reducing the quantity produced.[3]

This paper studies price discrimination in the electricity market. The standard model can be used to analyze price discrimination when transmission capacities are very large. If transmission capacities are intermediate or small, then the standard model can no longer be used.

Therefore this paper extends the standard model in two ways:

1. It assumes that the total transportation capacity is limited. Transmission is a scarce good, and access to the line is auctioned. The monopolist and the arbitrageurs buy transmission in an auction.[4]

2. The monopolist has different production costs in each region.

Welfare effects were ambiguous in the standard model, and it, therefore, does not come as a surprise that this is also the case in the extended model. However, the intuition is no longer the same.

We show in the extended model that allocational efficiency requires that the price difference is equal to the production cost difference. Arbitrage does *not* automatically increase *allocational efficiency*, as it could decrease the price difference too much. Again the *output* effect is ambiguous. Depending on the particular situation, the monopolist increases or decreases total production. As a consequence, the total welfare effect, which is the sum of both effects, can go either way.

For linear demand functions, we make some precise predictions. If demand functions are similar and the difference in production costs significant, then arbitrage decreases welfare. On the other hand, if the production cost differences are small and demand functions different, then arbitrage increases welfare.

Outline of the paper. Section 2 reviews the standard model, Section 3 discusses the extensions of the standard model, which is solved in section 4. The relevance for the electricity market is explained in section 5. Section 6 concludes the paper.

[3]This paper neglects the free riding argument against arbitrage, which states that arbitrageurs free ride on the investments made by the monopolist in local marketing, services *etc*.

[4]To simplify the exposition we assume that the capacity of the transmission line is small and that the price of transmission is positive. Willems (2002a) discusses intermediate transmission capacities.

2.2 Standard model

This section reviews the classical model of regional price arbitrage (Varian, 1985 and Tirole, 1988).

Consider two regions $i \in \{1, 2\}$. In each region there are price-taking consumers, represented by a downward sloping and concave demand function $h_i = h_i(p)$. Transport between the two regions is costless. The monopolist has constant production costs c_L is both regions.[5]

2.2.1 No arbitrage

If there is no arbitrage between the regions (index NA) then the monopolist can set a different price in each region. The profit of the monopolist is equal to his revenue in each market $h_i(p_i)p_i$ minus his production costs for each market $h_i(p_i)c_L$. He maximizes the following objective function:[6]

$$\max_{p_1,p_2} p_1 h_1(p_1) + p_2 h_2(p_2) - \{h_1(p_1) + h_2(p_2)\}c_L$$

The monopolist chooses the local monopoly price in each region:

$$p_1^{NA} = p_1^m(c_L) \tag{2.1}$$
$$p_2^{NA} = p_2^m(c_L) \tag{2.2}$$

with

$$p_i^m(c_L) \equiv \arg\max_p h_i(p)(p - c_L) \quad i = 1, 2 \tag{2.3}$$

This price is determined by the standard inverse elasticity rule:

$$\frac{p_i^m(c_L) - c_L}{p_i^m(c_L)} = \frac{1}{\varepsilon_i(p_i^m(c_L))} \quad i = 1, 2 \tag{2.4}$$

with $\varepsilon_i(p_i) = -p_i \frac{h_i'(p_i)}{h_i(p_i)}$ the demand elasticity in region i.

For explanatory convenience we will assume from now on that the price in region 1 is higher than the price in region 2.

2.2.2 Arbitrage

If there is arbitrage between the regions (index A) and consumers assign the same value to goods obtained from arbitrageurs as to goods obtained from the monopolist, then there will be uniform prices in both regions[7]

$$p = p_1 = p_2 \tag{2.5}$$

[5]With costless transportation it does not matter where the production is located.

[6]It is assumed that both markets will be supplied with a positive quantity.

[7]In a lot of industries, consumers value the sales of the monopolist (the authorized seller) higher than the goods from the arbitrageurs (unauthorized re-seller, parallel importer). This could be because of different packing, warranty *etc.* Ahmadi and Yang (2000) show that in that case, it is profitable for the monopolist to have some arbitrage, as it helps him to price discriminate consumers on the basis of their valuation of the (perceived) quality of the goods.

A price difference would allow arbitrageurs to make a profit by buying electricity in one region and selling it in the other region.

The monopolist now maximizes his objective function

$$\max_{p_1,p_2} p_1 h_1(p_1) + p_2 h_2(p_2) - \{h_1(p_1) + h_2(p_2)\}c_L \tag{2.6}$$

subject to the arbitrage constraint: $p = p_1 = p_2$.

The monopolist chooses the price as if he was supplying one aggregate market:

$$p_1^A = p_2^A = p_{tot}^m \tag{2.7}$$

with

$$p_{tot}^m \equiv \arg\max_p \ \{h_1(p) + h_2(p)\}(p - c_L) \tag{2.8}$$

Using demand elasticities, this price can also be written as:

$$\frac{p_{tot} - c_L}{p_{tot}} = \frac{1}{\theta_1 \varepsilon_1 + \theta_2 \varepsilon_2}$$

with $\theta_i = \frac{h_i(p)}{h_1(p)+h_2(p)}$ the relative size of market i.

2.2.3 Welfare effect: two components

This subsection shows that the welfare impact of arbitrage can be decomposed in an *allocative* and an *output* effect.

Define welfare as gross consumers's surplus (CS) minus production cost. Welfare can be written as a function of p_1 and p_2 :

$$W(p_1, p_2) = CS_1(p_1) + CS_2(p_2) - c_L(h_1(p_1) + h_2(p_2)) \tag{2.9}$$

Gross consumers surplus in region i is the area under the inverse demand function:

$$CS_i(p_i) = \int_0^{h_i(p_i)} h_i^{-1}(t)dt \tag{2.10}$$

In order to decompose welfare in the allocative and the output effect, welfare is rewritten as a function of total production $h = h_1(p_1) + h_2(p_2)$, and the regional price difference $\tau = p_1 - p_2$ *i.e.*

$$W(h, \tau) \tag{2.11}$$

The marginal effects of the total quantity and the price difference are given by: (Appendix 2.A)

$$\frac{\partial W}{\partial h} = p_1 \sigma_1 + p_2 \sigma_2 - c_L \tag{2.12}$$

$$\frac{\partial W}{\partial \tau} = -\rho \tau \tag{2.13}$$

with $\sigma_i = \frac{h_i'(p_i)}{h_1'(p_1)+h_2'(p_2)}$ and $\frac{1}{\rho} = -\left(\frac{1}{h_1'(p_1)} + \frac{1}{h_2'(p_2)}\right)$, $(0 \leq \sigma_i \leq 1$ and $\rho > 0)$.

They express the marginal welfare effect of one variable, keeping the other variable fixed. Equation 2.12 describes the *output effect* and 2.13 the *allocational efficiency* component. The logic behind the equations is as follows.

Equation 2.12 gives the welfare effect of a marginal increase in production (and thus consumption). Increasing production with one unit costs society c_L. The extra consumption is shared between the regions, *i.e.* consumption in region 1 increases with σ_1 and consumption in region 2 increases with σ_2 (with $\sigma_1 + \sigma_2 = 1$).[8]

The value for society of one unit extra consumption in region i is equal to p_i. The total effect on the consumers' surplus is therefore $(p_1\sigma_1 + p_2\sigma_2)$.[9]

Equation 2.13 shows the marginal welfare effect of the price difference τ. In order to increase the price difference τ with one unit, we need to shift ρ units of consumption of region 1 to region 2.[10] The welfare cost of one unit of consumption less in region 1 is p_1. The welfare value of one unit of extra consumption in region 2 is p_2. Shifting ρ units from region 1 to region 2 decreases welfare with $\tau\rho$. In the optimum, the marginal effect should be zero $\frac{\partial W}{\partial \tau} = \rho\tau = 0$. This implies that the price difference is zero.[11]

2.2.4 Welfare effect: linear demand

As a special case, this subsection considers linear demand functions of the form $h_i(p) = \alpha_i - \beta_i p$ $(\alpha_i > 0,\ \beta_i > 0)$. Without arbitrage the monopolist then sets

$$p_i^{NA} = \frac{\alpha_i}{2\beta_i} + \frac{c_L}{2}. \tag{2.14}$$

With arbitrage, the solution becomes

$$p_i^{A} = \frac{\alpha_1 + \alpha_2}{2(\beta_1 + \beta_2)} + \frac{c_L}{2}. \tag{2.15}$$

We consider now the *output* and the *allocational efficiency effect*.

It can be shown that for linear demand, total production h is equal with and without arbitrage:

$$h^A = h^{NA} = \frac{1}{2}[h_1(c_L) + h_2(c_L)] \tag{2.16}$$

[8]More precisely, σ_i is the marginal increase in consumption in region i, with a constant price difference. $\sigma_i = \left.\frac{\partial h_i}{\partial h}\right|_\tau$

[9]The monopolist chooses a production level which is lower than the social optimal. Total production has a positive impact on welfare $\left(\frac{\partial W}{\partial h} > 0\right)$ but at a decreasing rate $\left(\frac{\partial^2 W}{\partial h^2}(h) < 0\right)$

[10]More precisely, ρ is the marginal decrease of local consumption in region 1, when total production is kept constant $\rho = -\left.\frac{\partial h_1}{\partial \tau}\right|_h = \left.\frac{\partial h_2}{\partial \tau}\right|_h$.

[11]The marginal effect of the price difference τ is downward sloping $\left(\frac{\partial^2 W}{\partial \tau^2} < 0\right)$.

The price difference is zero with arbitrage,

$$\tau^A = 0 \tag{2.17}$$

and equal to $\frac{1}{2}\chi$ without arbitrage:

$$\tau^{NA} = \frac{1}{2}\chi \tag{2.18}$$

with $\chi = \frac{\alpha_1}{\beta_1} - \frac{\alpha_2}{\beta_2}$. The parameter χ is a measure of the difference in demand functions in region 1 and region 2.[12]

If the demand functions are equal, then the monopolist will set the same price in both regions. If demand in region 1 is less elastic than in region 2, the monopolist will set a higher price in region 1 then in region 2.

If we apply the intuition, then it is clear that arbitrage is welfare improving: total production does not change, but the allocation is more efficient with arbitrage.

2.3 Extending the model

This section adds some new features to the standard model.

2.3.1 First extension: costly arbitrage

In Section 2 we discussed two extreme cases:

In the *absence of arbitrage*, the market was perfectly 'sealed'. The monopolist could set any price in the two markets, without having leakage from one market to the other market. With *arbitrage*, the monopolist could only set a uniform price as any price difference would be arbitraged away.

This section introduces arbitrage that does not eliminate the regional price difference. The monopolist can set different prices in the two markets, but some 'leakage' due to arbitrage will occur. Arbitrageurs will buy goods in the high priced region and sell it in the low price region. Now we have imperfect sealing of the markets.

Let $x_A(p_1, p_2)$ be the amount of goods that arbitrageurs trade from region 2 to region 1, when the price in region one is p_1 and the price in region two is p_2. As above we assume that the price in region 1 is the highest.

If the monopolist sets the prices p_1 and p_2, then his sales s_1 and s_2 in region 1 and region 2 become

$$s_1(p_1, p_2) = h_1(p_1) - x_A(p_1, p_2) \tag{2.19}$$
$$s_2(p_1, p_2) = h_2(p_2) + x_A(p_1, p_2) \tag{2.20}$$

[12] Above we assumed that the price in region 1 was higher than in region 2 without arbitrage, $\tau^{NA} > 0$. For linear demand this implies that we assume that $\chi > 0$.

His profit is equal to

$$s_1(p_1, p_2)(p_1 - c_L) + s_2(p_1, p_2)(p_2 - c_L) \tag{2.21}$$

Models of the type 2.21 have been studied before.[13] It is then typically assumed that the demand function s_i in region i depends continuously on the prices in region 1 and region 2, *i.e.* it is assumed that cross-price effects are present.

Substituting the amount of arbitrage in the levels of sales, the profit function rewrites as:

$$h_1(p_1)(p_1 - c_L) + h_2(p_2)(p_2 - c_L) - x_A(p_1, p_2)\tau \tag{2.22}$$

with $\tau = p_1 - p_2$, the regional price difference.

Comparing the profit function with the one in section 2.2, an extra term is added: $-x_A \cdot \tau$. This is the revenue lost to the arbitrageurs.

One reason why arbitrage does not eliminate the price difference between the regions, is the fact that transportation is costly: Assume that to transport x units from region 2 to region 1 the total cost is equal to $T(x)$. If arbitrage is perfectly competitive, then the marginal transportation cost and the regional price difference will be equalized.

$$\tau = p_1 - p_2 = T'(x) \tag{2.23}$$

The amount that the arbitrageurs will arbitrage is the inverse of the marginal cost function:

$$x_A(p_1, p_2) = T'^{-1}(p_1 - p_2) \tag{2.24}$$

Several functional forms can be chosen for the transportation cost function. Chapter 3 looks at the case where the transportation cost are linear: $T(x) = t \cdot x$. This is also the assumption taken in Wright (1993).

Here, we look at a special form of transportation costs which is typical for the electricity market. Transportation is costless[14], but limited by the thermal transmission constraint of the transmission line that connects both regions:

$$x \leq k \tag{2.25}$$

with k the thermal capacity of the line.

If transmission capacity is large, the standard model is obtained. Arbitrage will equalize the prices in both regions.

If transmission capacity is smaller than the demand for transmission, it becomes a scarce good with a positive price. Often access to the transmission line is auctioned in order to reach an efficient allocation of the available capacity. The network operator, being in charge of operating transmission lines, will sell transmission rights. These rights give their owners the right

[13] See for example Lovel and Wertz (1981) and Varian (1992).

[14] We neglect the losses on the network.

to transport electricity on that line. The price of the transmission rights will be denoted by τ^t.

If there are arbitrageurs, they will drive up the price of the transmission rights τ^t until it equals to regional price difference $\tau = p_1 - p_2$.

In equilibrium, arbitrage will satisfy the following relations:

$$\begin{array}{ll} x_A(p_1, p_2) = k & \text{if } \tau > 0 \\ 0 \leq x_A(p_1, p_2) \leq k, & \text{if } \tau = 0 \end{array} \tag{2.26}$$

2.3.2 Second extension: cost differences

This subsection adds a second extension to the model. It is assumed that the monopolist has different production costs in each region.

This makes the model richer as there are now two reasons to use transmission capacity: price arbitrage by the consumers and cost arbitrage by the monopolist.

We will assume that the marginal production cost c_H in region 1 is larger than the cost c_L in region 2 ($c_H - c_L = \Delta c > 0$).

Given that transmission capacity is available, and that there are generation cost differences, the monopolist has two extra decision variables: the location where he produces, and the amount of transmission x_M that he buys.[15]

Price of the transmission rights

The price for transmission rights paid by the monopolist will depend on whether arbitrage is possible or not.

In the *absence of arbitrage*, transmission capacity can be bought at a zero price ($\tau^t = 0$). The monopolist is the only player in the market, and, therefore, existing regional price differences cannot be exploited by others. Of course, the total amount of transmission capacity he can buy needs to be smaller or equal than the available transmission capacity k.

$$x_M \leq k \tag{2.27}$$

With *arbitrage*, the monopolist will have to pay a price equal to the regional price difference.

If the monopolist sets a positive price difference, arbitrageurs will buy the remaining transmission rights $x_A = k - x_M$, and drive up the price of the transmission rights until $\tau^t = \tau$.

If the price difference is zero, arbitrageurs are indifferent in the amount of transmission rights that they buy, but the total quantity needs to be technically feasible ($x_A + x_M \leq k$).

[15] Of course these two decisions are closely linked with each other.

In equilibrium, arbitrage will satisfy the following constraints:

$$\begin{array}{ll} x_A(p_1,p_2) = k - x_M & \text{if } \tau > 0 \\ 0 \leq x_A(p_1,p_2) \leq k - x_M & \text{if } \tau = 0 \end{array} \tag{2.28}$$

Note the similarity with equation 2.26.

We assume that if the monopolist buys transmission rights, then he is obliged to use them. Buying transmission rights without using them is called 'withholding'. In most electricity markets this is forbidden as it could lead to strategic behavior of the players.[16]

Profit function of the monopolist

In region 1 and region 2 the monopolist sells s_1 and s_2. His revenue equals to

$$\text{Revenue} = s_1 p_1 + s_2 p_2 \tag{2.29}$$

Sales in region 1 are provided by producing q_1 locally, and by importing x_M units from region 2:

$$s_1 = q_1 + x_M \tag{2.30}$$

Production in region 2 is equal to the sales in region 2 plus the export to region 1.

$$q_2 = s_2 + x_M \tag{2.31}$$

The production costs of the monopolist are equal to $q_1 c_H + q_2 c_L$, which rewrites to

$$\text{Production Cost} = s_1 c_H + s_2 c_L - x_M \Delta c \tag{2.32}$$

The last term $x_M \cdot \Delta c$ is the cost reduction of a shift of x_M production units of the high cost region to the low cost region.

The monopolist needs to pay $\tau^t x_M$ for obtaining the transmission rights:

$$\text{Transport cost } = \tau^t x_M \tag{2.33}$$

The profit of the monopolist equals revenue minus production and transportation costs:

$$\pi = s_1(p_1 - c_H) + s_2(p_2 - c_L) + x_M \Delta c - x_M \tau^t \tag{2.34}$$

Given the level of arbitrage x_A and the goods' balances (2.19 and 2.20) profit rewrites as

$$\begin{aligned} \pi = {} & h_1(p_1)(p_1 - c_H) + h_1(p_1)(p_2 - c_L) && (2.35) \\ & + (x_M + x_A)\Delta c - x_A \tau - x_M \tau^t && (2.36) \end{aligned}$$

with $\tau = p_1 - p_2$, the price difference. It is instructive to analyze the different terms of the objective function:

[16] Willems (2002a) analyzes the case when withholding is allowed.

- The first two terms is the local profit the monopolist makes if all electricity is produced locally and consumed locally.
- The third term is the gain in production efficiency, as $x_M + x_A$ units of electricity are produced in country 2 instead of country 1.
- The fourth term is the loss of sales, to consumers who do not buy all electricity locally but buy some electricity from the arbitrageurs.
- The fifth term is the cost of buying transmission capacity.

This profit function covers several cases:

If the *absence of arbitrage,* we have by definition that $x_A = 0$. The monopolist can then buy transmission capacity at a price equal to zero $\tau^t = 0$ as long as sufficient transmission capacity is available. The profit function of the monopolist (No arbitrage, NA) is

$$\pi^{NA} = h_1(p_1)(p_1 - c_H) + h_2(p_2)(p_2 - c_L) - x_M \Delta c \tag{2.37}$$

$$x_M \leq k \tag{2.38}$$

With *arbitrage*, the price for transmission rights is equal to the regional price difference $\tau^t = \tau$. The profit function of the monopolist (Arbitrage, A) becomes

$$\pi^A = h_1(p_1)\,(p_1 - c_H) + h_2(p_2)\,(p_2 - c_L) + (x_M + x_A)\,(\Delta c - \tau) \tag{2.39}$$

Note

The results of the model are driven by costs differences at the production side of the market. The two markets could also have demand side specific cost differences (marketing, distribution *etc.*). As these types of costs are related with the point of sales, and not the point of production, they do no influence the production location of the monopolist.[17]

2.4 Extended Model

2.4.1 No arbitrage

The monopolist maximizes his profit function 2.37. As transmission capacity is small he will use the full capacity of the line to substitute expensive generation in region 1 with cheap generation in region 2 ($x_M = k$).

$$\pi^{NA} = h_1(p_1)(p_1 - c_H) + h_2(p_2)(p_2 - c_L) - k\Delta c \tag{2.40}$$

[17] In order to model demand side specific costs, one should examine whether arbitrageurs incur these costs as well, and whether they free ride on the expenses of the monopolist. This remains for further research.

The optimal prices in region 1 and region 2 are the local monopoly prices, taking into account the local production costs:

$$p_1 = p_1^m(c_H)$$
$$p_2 = p_2^m(c_L)$$

We assume that region 1 has the highest price. $(p_1^m(c_H) > p_2^m(c_L)$.

If both regions have the same concave demand function: $h_1(\cdot) = h_2(\cdot) = \tilde{h}(\cdot)$, then this will be the case: The monopolist shifts cost differences only partially through to his consumers $0 < \frac{\partial p^M}{\partial c} < 1$. The high cost region has the highest price, but the price difference is smaller than the cost difference:

$$0 < p^M(c_H) - p^M(c_L) < \Delta c. \tag{2.41}$$

2.4.2 Arbitrage

The monopolist maximizes his profit function 2.39. Assuming binding transmission capacity $(x_M + x_A = k)$, this rewrites as:

$$h_1(p_1)(p_1 - c_H) + h_2(p_2)(p_2 - c_L) + k(\Delta c - \tau) \tag{2.42}$$

Clearly his objective function depends on p_1 and p_2. Changing the price p_i has an impact on the regional profit $h_i(p_i)(p_i - c_j)$ but also on the total transmission cost $k\tau$.

The monopolist will set the prices

$$p_1^A = p_1^- \tag{2.43}$$
$$p_2^A = p_2^+ \tag{2.44}$$

where p_1^-, p_2^+ are defined as

$$p_1^- \equiv \arg\max_p \{h_i(p)(p - c_H) - kp\} \tag{2.45}$$
$$p_2^+ \equiv \arg\max_p \{h_i(p)(p - c_L) + kp\} \tag{2.46}$$

These prices would be optimal for a monopolist with two types of forward contacts. In region 2 the monopolist sold k forward contracts on the price p_2. And in region 1 he bought k contracts on the price p_1.[18]

Using the demand elasticity these prices can be written as:

$$\frac{p_2^+ - c_L}{p_2^+} = \frac{1}{\varepsilon_2} + \frac{k}{\varepsilon_2\ h_2(p_2^+)} \tag{2.47}$$
$$\frac{p_1^- - c_H}{p_1^-} = \frac{1}{\varepsilon_1} - \frac{k}{\varepsilon_1\ h_1(p_1^-)} \tag{2.48}$$

[18]These two forward contracts on the regional energy market can also be interpreted as one forward contract on transmission rights.

Arbitrage will force a profit maximizing monopolist to decrease the price difference relative to the no arbitrage case. The price in region 2 will increase while the price in region 1 will decrease. Note that, with $k = 0$, the monopolist would set the same prices as without arbitrage. This is logical as arbitrage is impossible without transmission.

$$\lim_{k \to 0} p_1^A = p_1^{NA} \tag{2.49}$$

$$\lim_{k \to 0} p_2^A = p_2^{NA} \tag{2.50}$$

2.4.3 Welfare effect: two components

In Section 2.2.3 we showed that for the standard, unconstrained capacity model. welfare could be written as a function of the total production level h, and the regional price difference τ. With k the capacity of the transmission line, we can now write welfare as $W^*(h, \tau, k)$.

Using the inverse function theorem the marginal effects of these variables can be written as (Appendix 2.A):

$$\frac{\partial W^*}{\partial h} = (p_1 - c_H)\sigma_1 + (p_2 - c_L)\sigma_2 \tag{2.51}$$

$$\frac{\partial W^*}{\partial \tau} = \rho\ [\Delta c - \tau] \tag{2.52}$$

$$\frac{\partial W^*}{\partial k} = \Delta c \tag{2.53}$$

The first equation shows the marginal welfare effect of increasing total consumption h. σ_i is the marginal change of consumption in region i when total output increases, while keeping the price difference between the regions constant. The welfare effect of a consumption increase in region 1 is equal to $(p_1 - c_H)$, because it has to be produced locally, given that the transport k is not changed. For the same reason, the effect of a consumption increase in region 2 is equal to $(p_2 - c_L)$.

The second equation shows that, the welfare effect of a marginal change of the price difference is proportional to $\Delta c - \tau$. If ρ units of demand are shifted from region 1 to region 2, also ρ units of production needs to be shifted from region 1 to region 2 as the transmission capacity is assumed to be binding. At the margin, shifting demand decreases consumers surplus with $\rho\tau$, and decreases production costs with Δc. In the optimum, demand should be allocated such that the price difference equals the cost difference.

The last equation shows that a marginal increase in the transmission capacity would result in a welfare increase ($\Delta c > 0$), because extra low cost production can be used to replace high cost production in region 1.

2.4.4 Welfare: linear demand

This subsection illustrates the model under the assumption of linear demand.

Without arbitrage, the monopolist sets prices equal to

$$p_1^{NA} = \frac{\alpha_1}{2\beta_1} + \frac{c_H}{2} \tag{2.54}$$

$$p_1^{NA} = \frac{\alpha_2}{2\beta_2} + \frac{c_L}{2}. \tag{2.55}$$

With arbitrage prices become

$$p_1^{A} = \frac{\alpha_1}{2\beta_1} + \frac{c_H}{2} - \frac{k}{2\beta_1} \tag{2.56}$$

$$p_2^{A} = \frac{\alpha_2}{2\beta_2} + \frac{c_L}{2} + \frac{k}{2\beta_2}. \tag{2.57}$$

In both regimes, total production is equal to

$$h = \frac{1}{2}[h_1(c_L) + h_2(c_L)] \tag{2.58}$$

This feature is due to the linear demand assumption. A welfare comparison should therefore only look to the price difference τ.

Recall that the optimal price difference is equal to the cost difference between the two regions:

$$\tau^{opt} = \Delta c \tag{2.59}$$

Without arbitrage the price difference is equal to

$$\tau^{NA} = \frac{\Delta c}{2} + \frac{\chi}{2} \tag{2.60}$$

When the two demand functions are similar (χ close to zero), the price difference is about half the cost difference and the price difference is lower than welfare optimal.

With arbitrage, the price difference is equal to

$$\tau^{A} = \frac{\Delta c}{2} + \frac{\chi}{2} - \frac{k}{\rho} \tag{2.61}$$

Arbitrage makes price discrimination costly for the monopolist, and he will set a lower price difference with arbitrage than without

$$\tau^{NA} > \tau^{A} \tag{2.62}$$

For similar demand functions we have thus

$$\tau^{opt} > \tau^{NA} > \tau^{A} \tag{2.63}$$

Arbitrage thus decreases welfare. This is summarized in the following proposition:

Proposition 1. *For similar linear demand functions ($0 \leq \chi < \Delta c$) and with binding capacity constraints arbitrage is welfare decreasing.*

Proof. The proof follows from the discussion above. □

Corollary 2. *If there is perfect competition in the low cost region 2 and linear demand in both regions, arbitrage is always beneficial.*

Proof. If there is perfect competition in the low cost region 2, the *residual* demand function for the monopolist is perfect elastic $\beta_2 \to \infty$ and the price in the low cost region is $\frac{\alpha_2}{\beta_2} = c_L$. The price in the high cost region 1 is always above c_L. Unbundling gives an incentive to decrease the price difference between the regions, and hence decreases the price in region 1, and is always optimal. □

2.4.5 Welfare: non-linear demand

This subsection studies the effect of arbitrage on welfare with non-linear demand for small transmission capacities. In the extreme case of zero transmission capacity ($k = 0$), there is obviously no arbitrage, and the monopolist will set the prices:

$$p_1^A = p_1^{NA} = p_1^M(c_H) \tag{2.64}$$
$$p_2^A = p_2^{NA} = p_2^M(c_L) \tag{2.65}$$

In order to compare the two regimes we make a first order approximation of the welfare function around $k = 0$, taking into account the behavior of the monopolist. We obtain the following proposition:

Proposition 3. *Define the function $f_i(p) = \frac{h_i''(p)}{h_i'(p)} - 2\frac{h_i'(p)}{h_i(p)}$. Arbitrage increases welfare for transmission capacities close to zero ($k \to 0$) iff*

$$f_2(p_2^m(c_L)) > f_1(p_1^m(c_H)) \tag{2.66}$$

Proof. See Appendix 2.B □

For equal demand the following corollary immediately follows.

Corollary 4. *If two regions have identical concave demand functions $h_i(\cdot) = \widetilde{h}(\cdot)$ and $f' < 0$ (> 0) for all p, than arbitrage increases (decreases) welfare.*

Proof. Above, we showed that if demand functions are identical, that the low cost region has the lowest price $\tilde{p}^m(c_L) < \tilde{p}^m(c_H)$. Using the fact that $f'(p) > 0$ the results follow directly from proposition 3. □

The practical applications of this corollary is limited by the fact that the slope of f involves third order derivatives of the demand functions.

2.5 Discussion

2.5.1 What type of markets?

The paper considers a very specific set-up: a single monopolist, supplying a homogenous product to two geographically separated markets. Production costs and demand conditions are different in each market. A line with a limited transport capacity connects both markets.

The model can be applied to the electricity market, where both transmission capacity constraints and differences in production costs are important. The existing transmission lines that interconnect countries, are designed to transport only emergency power during a contingency. With liberalization, interconnectors are also used to arbitrage on regional price differences. As a result some of the lines are highly congested.

The applicability of the current model to other markets is restricted as most sectors do not have strict limits on the amount of transportation, and because there are no cost differences at the production side. The results of the model do not hold if there are only cost differences at the demand side like marketing costs and costs for applying to local regulation.

2.5.2 Congestion in electricity markets

This subsection discusses some of the related literature on electricity markets.

Joskow and Tirole (2000) and Gilbert *et al.* (2002) model the microstructure of the transmission rights market. They show that some auctions give perfect arbitrage ($\tau = \tau^t$) and others imperfect arbitrage ($0 < \tau^t < \tau$). Each type of auction has therefore a different impact on welfare. Chapter 4 explains their models in more detail.

One of the drawbacks of their models is that they assume that all strategic generators are located at one end of the line, while production at the other end is perfectly competitive. The contribution of this paper is that it shows that their results cannot be extended to cases where strategic production is located at both ends of the line.

Borenstein *et al.* (1998) discuss a Cournot generation duopoly. They assume that each player has production in one of the regions, and that arbitrage is perfect. Insufficient transmission capacity decreases the competition in electricity market. Our paper is different, as we study the impact of imperfect arbitrage, while they only look at perfect arbitrage.

2.6 Conclusion

The main contribution of this paper is to extend to standard model of third degree price discrimination. The paper adds limited transportation capacity and differentiated production costs. It shows results that are fundamentally different from the standard model.

As a special case, it considers linear demand functions. In that case, arbitrage decreases welfare when transportation capacity is low, generation costs are different and demand conditions similar.

The model can be applied to the electricity market where both transmission capacity constraints and differences in production costs are important.

The following policy implications can be derived:

- If a transmission line has a small capacity and production costs are different between two regions, then it is sometimes better to let the monopolist manage the transmission line.
- If transmission capacity is sufficiently large, then auctioning of transmission capacity is optimal (linear demand functions).
- A transmission line that starts in a competitive low cost region can always be auctioned.

Of course, the main problem is the market power of the monopolist. The model shows that making the transmission market more efficient does not need to increase welfare. It should therefore remain one of the main objectives to reduce generation market power.

2.6.1 Possible extensions

The paper assumes that the network constraint is always binding. It neglects the fact that consumption and generation can not become negative. Willems (2002a) solves the model without these constraints.

Extensions of the model to a *more complex network* are cumbersome, given the non-linear constraints in the optimization problem for the monopolist.

Extending the model from a monopoly to an *oligopoly model* requires an extra assumption on the variables that are set by the generators: quantities, supply functions, *etc.*[19]

In principle one would expect to see a similar result in a model where all players have generation capacity at both ends of the line. Arbitrage will give them an incentive to reduce the regional price difference. Again, the price difference might become too small.

The paper assumes *strict capacity limits* for the transmission line, which is valid in the short-run. However, in the long-run transmission capacity is

[19] There is however a problem in using the Cournot assumption in a decentralized market without arbitrage. If both players independently set their production quantities, it is no longer guaranteed that the transmission constraints are satisfied. One way out to solve this problem is to assume a rationing rule (Chapter 5). Another way is to assume that generators are price takers in the generation market (Day *et al.,* 2002 and Chapter 6).

not fixed. A competitive transmission market, in which transmission prices reflect the regional price differences, might give investors an incentive to build extra transmission capacity. If transmission markets are not working well, only the monopolist will invest in new transmission capacity. This problem will be discussed in Chapter 3.

Appendix 2.A Welfare function

2.A.1 Standard model

Welfare W can be written as a function of p_1 and p_2. The marginal welfare effects of p_1 and p_2 are:

$$W^{p_1} = h_1'(p_1)(p_1 - c_L) \tag{2.67}$$
$$W^{p_2} = h_1'(p_2)(p_2 - c_L) \tag{2.68}$$

Welfare W can also be expressed as function of total production h and the regional price difference τ. The marginal welfare effects can be calculated using the implicit function theorem:

$$\begin{bmatrix} W^h \\ W^\tau \end{bmatrix} = \begin{bmatrix} \frac{\partial h}{\partial p_1} & \frac{\partial \tau}{\partial p_1} \\ \frac{\partial h}{\partial p_2} & \frac{\partial \tau}{\partial p_2} \end{bmatrix}^{-1} \begin{bmatrix} W^{p_1} \\ W^{p_2} \end{bmatrix} \tag{2.69}$$

2.A.2 Extended model

Welfare W can be written as a function of p_1, p_2, and k. The marginal welfare effects are:

$$W^{p_1} = h_1'(p_1)(p_1 - c_H) \tag{2.70}$$
$$W^{p_2} = h_2'(p_2)(p_2 - c_L) \tag{2.71}$$
$$W^k = \Delta c \tag{2.72}$$

Rewriting the welfare W as function of total production h, the regional price difference τ, and the transported capacity k, the marginal effects can be calculated as:

$$\begin{bmatrix} W^h \\ W^\tau \\ W^x \end{bmatrix} = \begin{bmatrix} \frac{\partial h}{\partial p_1} & \frac{\partial \tau}{\partial p_1} & 0 \\ \frac{\partial h}{\partial p_2} & \frac{\partial \tau}{\partial p_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} W^{p_1} \\ W^{p_2} \\ W^x \end{bmatrix} \tag{2.73}$$

with $\frac{\partial h}{\partial p_i} = h_i'(p_i)$, $\frac{\partial \tau}{\partial p_1} = 1$, and $\frac{\partial \tau}{\partial p_2} = -1$.

Appendix 2.B Proof of proposition 3

Define the level of welfare V under regime $l = A, NA$ as

$$V^l(k) = W(p_1^l(k), p_2^l(k), k) \quad l = A, NA \tag{2.74}$$

with $p_i^l(k)$ the price in region i that the monopolist sets in region i under regime l.

Welfare is equal under both regimes for $k = 0$:

$$V^A(0) = V^{NA}(0). \tag{2.75}$$

For small transmission capacities welfare can be approximated as

$$V^l(k) \simeq V^I(0) + k \cdot \frac{dV^I}{dk}(0) \tag{2.76}$$

where the marginal welfare effect can be calculated as $\frac{dV^l}{dk} = W^{p_1}\frac{dp_1^l}{dk} + W^{p_2}\frac{dp_2^l}{dk} + W^k$.

Without arbitrage, the marginal effect of transmission capacity is

$$\frac{dV^{NA}(0)}{dk} = \Delta c \tag{2.77}$$

With arbitrage, the marginal effect is

$$\frac{dV^A(0)}{dk} = \left[\frac{h_1''(p_1^A)}{h_1'(p_1^A)} + \frac{2}{p_1^A - c_H}\right]^{-1} - \left[\frac{h_2''(p_2^A)}{h_2'(p_2^A)} + \frac{2}{p_2^A - c_L}\right]^{-1} + \Delta c \tag{2.78}$$

Arbitrage is welfare improving when

$$\frac{dV^A}{dk}(0) > \frac{dV^{NA}}{dk}(0) \tag{2.79}$$

Rewriting this expression using the first order conditions of the monopolist around ($k = 0$)

$$h_2'(p_2^A)(p_2^A - c_H) + h_1'(p_1^A) = 0 \tag{2.80}$$

$$h_2'(p_2^A)(p_2^A - c_L) + h_2'(p_2^A) = 0 \tag{2.81}$$

one obtains easily that arbitrage is welfare improving when $f_2(p_2^m(c_L)) > f_1(p_1^m(c_H))$.

3

Third degree price discrimination with costly arbitrage.

A monopolist sells a homogenous good in two different countries with linear demand functions. He owns production plants in each country. In one country production costs are higher than in the other country and transportation is costly. The paper studies the effect of arbitrageurs on the total surplus in the market. In general, arbitrage increases welfare, however, if demand functions are similar, and the transportation cost significant but still smaller than the difference in production costs, arbitrage reduces total surplus.

3.1 Introduction

Consider a homogenous good that is produced and consumed in two countries. In each country there is a competitive market, where consumers and producers trade the good. Transport between the two countries is costly.

To this perfectly competitive world, we add one large multinational firm who owns production capacity in both countries. This firm behaves as a monopolist, and wants to maximize its profit. He sets prices taking into account his production costs and the demand elasticities.

In the *first part* of the paper, we assume that the monopolist can forbid arbitrage between the two countries. Only the monopolist can ship goods from one country to the other. The monopolist forecloses the transportation market. The optimal actions are derived for the monopolist.

In the *second part*, we assume that there is arbitrage on the locational price differences. Arbitrageurs will buy the good in low priced country, transport the good, and sell the good in the high priced country. As transportation

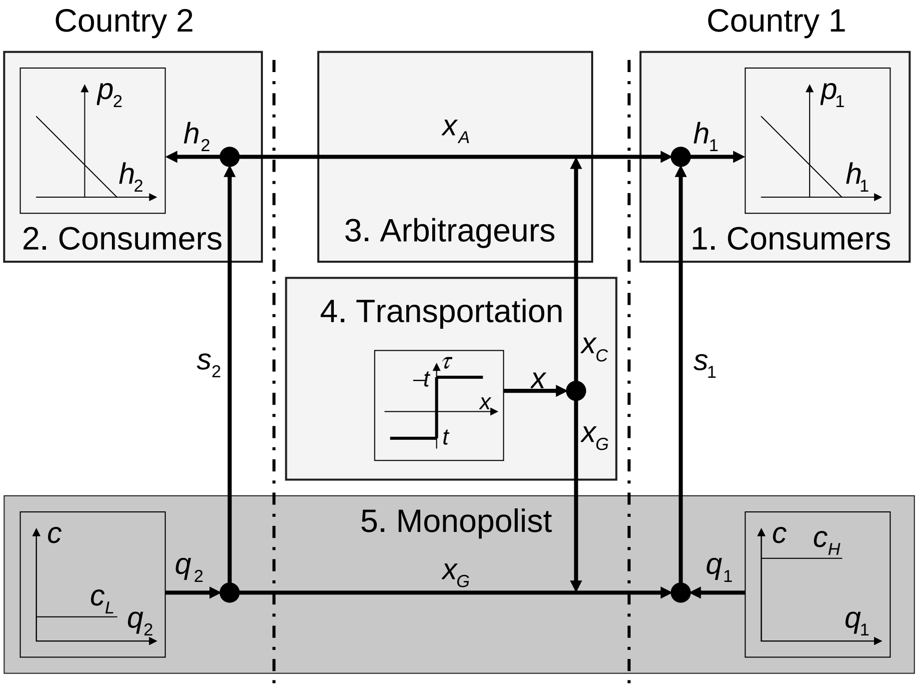

Figure 3.1: Schematic presentation of the model.

is costly, arbitrage will not eliminate the price difference completely.

The paper derives the optimal strategy of the monopolist. It is shown that he has to solve a mathematical program with equilibrium constraints (MPEC). This MPEC is solved, and the different types of equilibria are discussed.

Comparing welfare in the case with and without arbitrage we can conclude that in general arbitrage is welfare improving. However, when the transmission cost is just below the production cost difference, and demand functions are similar arbitrage is actually welfare decreasing.

Three numerical examples illustrate the solution of the model.

3.2 Description of the model

Figure 3.1 gives a schematic presentation of the model in the paper. The model considers two countries: country 1 and country 2. The left side of the figure presents country 2, the right side country 1. In the model there are 5 different agents: consumers in country 1 and 2, arbitrageurs, transporters and the monopolist. This section starts with a description of these agents.

In each country there are competitive *consumers* with a linear demand function:

$$h_i(p_i) = \alpha_i - \beta_i p_i \tag{3.1}$$

Define $\bar{p}_i$, the reservation price of consumers in country i :

$$\bar{p}_i \equiv h_i^{-1}(0) = \frac{\alpha_i}{\beta_i} \tag{3.2}$$

The consumers in region 1 buy x_A units from the arbitrageurs and s_1 units from the monopolist. In region 2 they buy s_2 units from the monopolist, but resell x_A units to the arbitrageurs. The good's balance for the consumers is:

$$\begin{aligned} s_1 + x_A &= h_1(p_1) \\ s_2 - x_A &= h_2(p_2) \end{aligned} \tag{3.3}$$

For simplicity we do not impose that consumers should consume a positive quantity.[1]

Arbitrageurs arbitrage on the price difference between the two countries. They buy x_A units in country 2 and sell it in country 1 (A negative x_A will denote transport from country 1 to country 2). They buy transportation in a competitive market at a price τ. Arbitrageurs trade until the price difference equals the price for transport.

$$\tau = \Delta p \tag{3.4}$$

with $\Delta p = p_1 - p_2$.

If the price difference between the regions is higher than the transportation price, the arbitrageurs will buy transportation capacity, buy goods in the cheapest country and sell the goods in the expensive country.

The monopolist is the only player in the model who behaves strategically, *i.e.* he is not a price taker. He has production capacity in each country. He produces q_i units in country i at constant marginal costs. The marginal production cost c_H in country 1 is larger than the cost c_L in country 2 ($c_H - c_L = \Delta c > 0$). Production should be non-negative $q_i \geq 0$, but there is no capacity constraint for production.

The monopolist buys x_G units of transportation, and transports x_G units from country 2 to country 1. He sells s_i units in country i at a price p_i. His good's balance in each country is (Figure 3.1):

$$q_1 = s_1 - x_G \tag{3.5}$$

$$q_2 = s_2 + x_G \tag{3.6}$$

The monopolist's profit is equal to:

$$\pi = p_1 s_1 + p_2 s_2 - c_1 q_1 - c_2 q_2 - \tau x_G$$

The first two terms are the sales in region 1 and 2, the third and fourth terms are the production costs, and the last term is the transmission cost for the generator.

[1] Interpretation: if the price is above the reservation value, ($p_i > \bar{p}_i$), some of the consumers will switch their role and become competitive fringe suppliers. This assumption does not change the main results of the paper.

It is assumed that production costs of the monopolist are below the reservation prices in the two countries ($\bar{p}_i > c_H$). This implies that the monopolist will always sell profitably in one of the two countries.

Substituting the good's balance (3.5 and 3.6), the profit function of the monopolist changes to:

$$\pi = h_1(p_1)\,(p_1 - c_H) + h_2(p_2)\,(p_2 - c_L) + x\Delta c - x_A\Delta p - x_G\tau \tag{3.7}$$

with $\Delta p = p_1 - p_2$, $\Delta c = c_H - c_L$.

The first two terms are the profits the monopolist makes if all electricity is produced and consumed locally. The third term is the gain in production efficiency, when x units of electricity are produced in country 2 instead of country 1. The fourth term is the loss of sales, when consumers do not buy all electricity locally but buy some electricity from the arbitrageurs. The fifth term is the cost of buying transportation.

Transporters sell x_G and x_A units of transportation to the monopolist and the arbitrageurs. In total they transport $x = x_A + x_G$ units from country 2 to country 1. A negative x means transportation in the other direction. The unit transportation cost is constant, and independent of the direction of transport. The total transportation cost is:

$$T(x) = t|x|. \tag{3.8}$$

Transporters are price takers. They maximize their profit given the price for transmission τ

$$\max_x \tau x - T(x) \tag{3.9}$$

They sell thus at marginal cost. The competitive supply function $\tau(x)$ of transport is described by the following equations (Figure 3.2):

$$\tau = t \Rightarrow x > 0 \tag{3.10}$$

$$-t \leq \tau \leq t \Rightarrow x = 0 \tag{3.11}$$

$$\tau = -t \Rightarrow x < 0 \tag{3.12}$$

Note that the transportation price becomes negative for negative levels of transportation.

3.3 Expensive transportation

Let us first look at an extreme case where transportation is very costly so it will not be used in any circumstance. This is the benchmark autarky model.

The monopolist will set in each country the local monopoly price:

$$p_1 = \frac{\bar{p}_1 + c_H}{2} \tag{3.13}$$

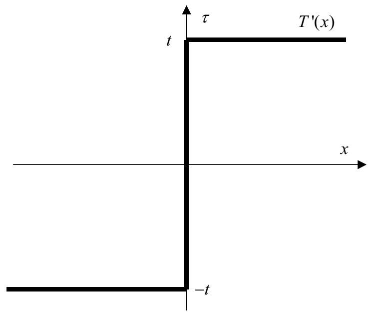

Figure 3.2: Competitive supply function of transport

$$p_2 = \frac{\bar{p}_2 + c_L}{2} \tag{3.14}$$

The price difference between the countries is equal to

$$\Delta p = \frac{\chi + \Delta c}{2} \tag{3.15}$$

with $\Delta p = p_1 - p_2$, $\chi = \bar{p}_1 - \bar{p}_2$ and $\Delta c = c_H - c_L$

This equation shows that there are two reasons why the monopolist would like to set a different price in each country. The first is the difference in demand functions in each country χ. The second is the difference in production costs Δc.

χ is a measure for the difference in demand conditions in the two regions. If demand conditions are similar in both countries, χ is close to zero. In this case, the only reason for the monopolist to set different prices is the cost difference. If χ is large and positive, the monopolist would like to set a higher price in country 1 than in country 2. If χ is negative and large $\chi < -\Delta c$, the monopolist would like to set a lower price in country 1 than in country 2.

3.4 No arbitrage

This section assumes that the monopolist can prevent arbitrage by the arbitrageurs. He could for example forbid consumers to resell their products. For the model this means that (1) arbitrageurs do not transport goods,

$$x_A = 0 \text{ and hence, } x = x_G \tag{3.16}$$

and that (2) the arbitrage constraint (3.4) does not have to be satisfied, the price of transmission might be larger, or smaller than the price difference.

$$\tau \gtrless \Delta p \tag{3.17}$$

If arbitrage is impossible, it becomes easier for the monopolist to price differentiate between the two countries.

In this section we assume that the arbitrageurs are not present. An alternative formulation would be one where the monopolist buys the transportation firms and denies the arbitrageurs access to transportation (*i.e.* Foreclosure of the transportation market).[2] In that formulation he incurs the cost of transmission himself. It can be shown that both formulations give the same outcome in our setting, because the supply function of transmission is perfectly elastic.

With increasing marginal transportation costs the two formulations are no longer be equivalent. If the monopolist owns the transportation sector, transportation will be used to ensure *production efficiency*. If the monopolist has to buy transportation, this is no longer the case. The monopolist will use his monopsony power and decreases demand for transportation in order to lower the price he pays for transportation.

The monopolist maximizes:

$$h_1(p_1)(p_1 - c_H) + h_2(p_2)(p_2 - c_L) + x(\Delta c - \tau) \tag{3.18}$$

subject to the supply function of transport

$$\tau = \tau(x) \tag{3.19}$$

and the positive production constraints $q_i \geq 0$ which can be rewritten as:

$$h_1(p_1) \geq x \quad (z_1) \tag{3.20}$$

$$h_2(p_2) \geq -x \quad (z_2) \tag{3.21}$$

The solution is very intuitive if we think of the interpretation where the monopolist owns all transportation. In that case it is clear that production will be efficient.

If the transport cost is smaller than the cost difference $(t < \Delta c)$, the monopolist will produce only in the low cost country 1, and import all goods into the high cost country 2. He sets a positive level of transport, $x = h_1(p_1) > 0$ and pays a price $\tau = t$ for it.

If the transport cost is larger than the cost difference $(\Delta c < t)$, the monopolist will produce everything locally, transport no goods, and choose the local monopoly price in each region.

The price in region 2 is the local monopoly price

$$p_2 = \frac{\bar{p}_2 + c_L}{2} \tag{3.22}$$

The price in region 1 is the monopoly price in region 1 given that production cost is equal to $\min\{c_L + t, c_H\}$

$$p_1 = \frac{\bar{p}_1 + \min\{c_L + t, c_H\}}{2} \tag{3.23}$$

[2]This assumes that entry in the transportation market is impossible.

3.5 Perfect arbitrage

This section assumes that there is perfect arbitrage $(\tau = \Delta p)$. Substituting the perfect arbitrage condition in equation 3.7 gives the monopolist's profit:

$$h_1(p_1)(p_1 - c_1) + h_2(p_2)(p_2 - c_2) + x\Delta c - x\tau \tag{3.24}$$

The monopolist maximizes profit subject to the arbitrage constraint

$$\tau = \Delta p \tag{3.25}$$

to the positive production constraints,

$$h_1(p_1) \geq x \tag{3.26}$$
$$h_2(p_2) \geq -x \tag{3.27}$$

and the competitive supply of transportation

$$\tau = \tau(x) \tag{3.28}$$

There are two difficulties in solving this optimization. First, the supply function $\tau(x)$ does not define a convex set. Second, the objective function is not concave due to the last term $x \cdot \tau$.

The monopolist has to choose a point on the supply function of transportation (presented in Figure 3.3). This supply function consists of three parts and two corner points: There can maximally be 5 local optima:[3]

- a local optimum on **part (1)** $(\tau = t,\ x > 0)$,
- **corner point (A)** $(\tau = t,\ x = 0)$,
- a local optimum on **part (2)** $(-t < \tau < t,\ x = 0)$,
- **corner point (B)** $(\tau = -t,\ x = 0)$,
- and a local optimum on **part (3)** $(\tau = -t,\ x < 0)$.

Appendix 3.A of the paper gives the optimal prices for each of the five optima, and the conditions under which each of them can be a local optima. The monopolist takes the local optimum that gives him the highest profit.

Which of these five is optimal depends on the value of the parameters, and is summarized in Figure 3.4.

On the Y-axis of the figure is the value of $\chi = \bar{p}_1 - \bar{p}_2$. This is the measure of the importance of demand conditions for the price differentiation (see above).

[3]Appendix 3.C shows that, once τ or x is fixed, that the remaining problem is well behaving. So there is maximally one local optimum on the line $\tau = t$ for strictly positive $x \geq 0$.

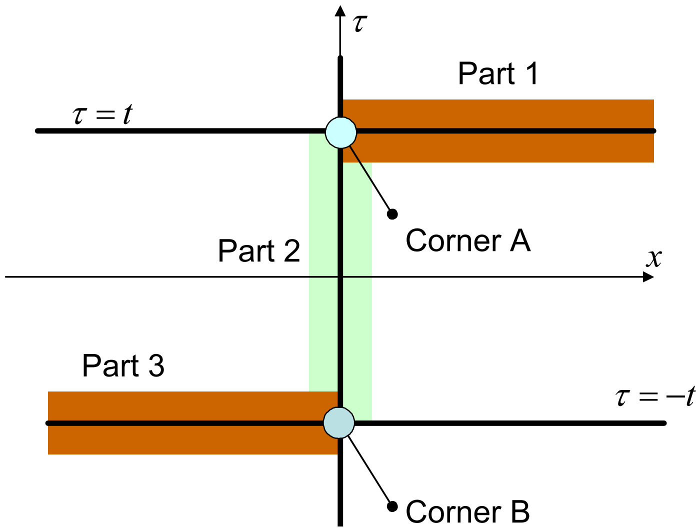

Figure 3.3: The supply function of transportation consists of 3 parts (1, 2, and 3) and 2 corner points (A and B).

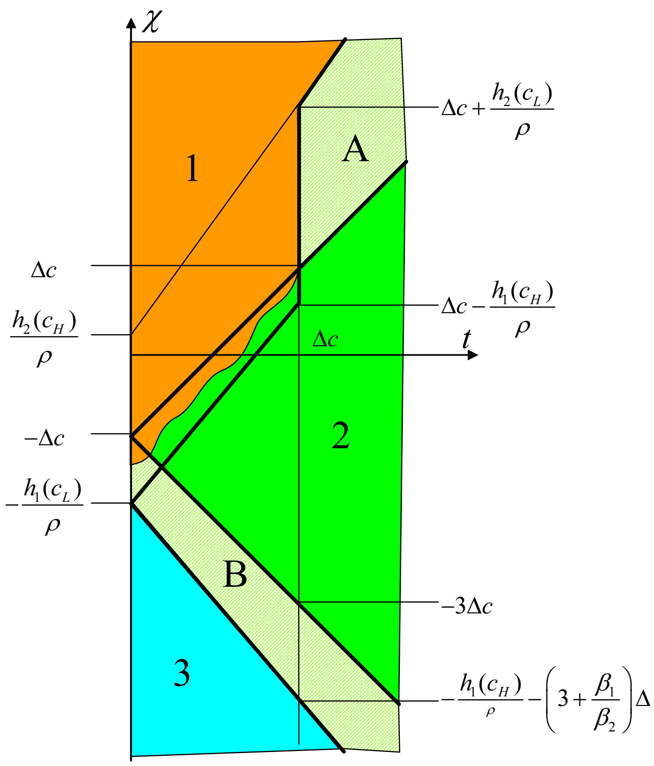

Figure 3.4: Type of equilibria for the different parameters.

On the X-axis is the parameter for transmission cost t. If t increases, arbitrage becomes costly.

The parameter ρ in the figure is a weighted average of the demand slopes in each country. (It can be interpreted as the slope of the demand function for transmission by the arbitrageurs, see also Chapter 2)

$$\rho = \frac{\beta_1 \beta_2}{\beta_1 + \beta_2} \tag{3.29}$$

There are several regions in the figure that we will explain now. The numbers 1, 2, and 3, and the letters A and B correspond with one of the five local optima we identified above.

For *large* χ, the monopolist will set the maximal positive price difference between the regions $\tau = t$, there is a positive transport from country 2 to country 1 (optimum on part 1 of the supply function).

For *small* χ, the monopolist sets the maximal negative price difference between the regions, and there is transport from the high cost country 1 to the low cost country 2 (optimum on part 3 of the supply function).

For χ *close to zero*, the monopolist can price discriminate, but sets a price difference that is smaller than the transportation cost (optimum on part 2 of the supply function). There is no transport.

In the hashed regions (regions A and B) the monopolist chooses one of the corner solutions.

The boundary between region 1 and region 2 depends on other parameters than χ and t, and is therefore represented by a zig zag line. The boundary lies between the thick line above and the thick line below of it.

Do these solutions guarantee an efficient production?

For equilibria on the part 3 of the supply function, goods are transported from the high cost country 1 to the high cost country 2. This is clearly not efficient. For equilibria on part 1 of the supply function, transport goes from the high cost country to the low cost country. This is efficient as long as the transportation cost t is smaller than the difference in production costs (left side of Figure 3.4). If the transportation cost is larger than the cost difference, transport is reducing production efficiency.

The boundary between region 1 and region 2 in Figure 3.4 jumps when t becomes larger than the cost difference. This is a consequence of the reduced production efficiency in region 1 for $t > \Delta c$.

3.6 Comparison Arbitrage - No arbitrage

This section compares arbitrage and no arbitrage. The comparison is made for the profit of the monopolist, the consumers' surplus, and total welfare.

The monopolist never prefers arbitrage. Without arbitrage, the arbitrage constraint drops out of the problem, and optimizing with less constraints gives never a lower profit.

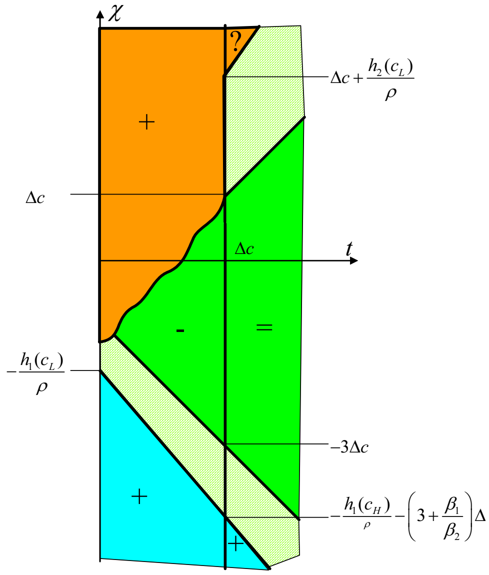

Figure 3.5: Welfare effect of allowing arbitrage. Plus sign: arbitrage increases welfare, minus sign: arbitrage decrease welfare. Questions mark: it depends upon the other parameters.

For *consumers* it all depends, some consumers will gain, other consumer will lose.

Define *welfare* as the sum of consumers surplus in country 1 and 2, and the monopolist's profit.[4]

$$W = CS_1 + CS_2 + \pi \tag{3.30}$$

The effect of arbitrage on the level of welfare is not clear cut, but depends on the specific parameters of the problem. The results are summarized in Figure 3.5. (For the calculations see the appendix). In the parameter regions that are marked with a plus sign, arbitrage is welfare increasing. In the regions with a minus sign, arbitrage is welfare decreasing. In the region with the equality sign, arbitrage has no effect. In regions with the question mark, no general results were found.

The picture illustrates the following conclusions: Arbitrage increases welfare in most cases. However, in one triangular region, arbitrage is welfare decreasing.

This happens when (1) the transport cost is positive ($t > 0$) but (2) smaller than the production cost difference ($t < \Delta c$) (3) demand in the two countries is similar (χ close to zero), or slightly more competitive in the high cost region ($\chi < 0$). These conditions can be written out more formally as follows:

[4]The surplus of the transporters is always equal to zero.

	EXAMPLE 1	EXAMPLE 2	EXAMPLE 3
$alpha_1$	2.00	1.60	0.50
$beta_1$	1.00	1.50	0.90
$alpha_2$	2.00	2.50	3.00
$beta_2$	1.00	1.10	1.10
c_H	1.00	1.00	0.50
c_L	0.50	0.00	0.00
t	0.25	0.76	0.20

Table 3.1: Parameters used in the three examples

Proposition 5. *If the parameters of the problem satisfy the following three conditions* $t < \Delta c$, $\chi > -\Delta c - 2t$ *and* $\chi < -\frac{h_1(c_L)}{\rho} + \left(2 + \frac{\beta_1}{\beta_2}\right) t$, *then arbitrage is welfare decreasing.*

Proof. If there is arbitrage, the monopolist's profit becomes maximal on part 2 of the supply function. If there is no arbitrage, the monopolist's profit becomes maximal on part 1 on the supply function. Calculating and comparing welfare shows that arbitrage decreases welfare. □

3.7 Numerical examples

Three numerical examples are used to illustrate the results. The parameters used for each example can be found in Table 3.1.

The three examples were all chosen such that $t < \Delta c$. The opposite case where the transportation cost is higher than the production cost difference is less interesting. Furthermore, each example corresponds with a different case in Figure 3.4. In example 1, transmission will be used from the low cost country to the high cost country (optimum on part 1 of the supply function). In example 2, transmission is not used (optimum on part 2 of the supply function). In example 3, transmission is used in the opposite direction, from the high cost country to the low cost country (optimum on part 3 of the supply function).

The results of the welfare calculations of the three models can be found in Table 3.2. The first rows give the prices that the monopolist sets in both countries, with and without arbitrage.

The last rows compares the welfare effects of arbitrage. In example 1 and in example 3 arbitrage is welfare improving. In example 2, arbitrage reduces welfare. This confirms the results of Figure 3.5.

In order to understand the intuition behind these results, we will look at the changes of transport x, total production $h = h_1(p_1) + h_2(p_2)$, and the price difference Δp. But first we will discuss how welfare is influenced by changes in these three parameters.

	EXAMPLE 1			EXAMPLE 2			EXAMPLE 3		
	Arbit.	No Arbit.		Arbit.	No Arbit.		Arbit.	No Arbit.	
P_1	1.13	1.38		1.03	0.91		0.72	0.38	
P_2	0.88	0.75		1.14	1.14		0.92	1.36	
P_1-P_2	0.25	0.63	?	-0.10	-0.23	>	-0.20	-0.99	>
delta c	*0.50*	*0.50*		*1.00*	*1.00*		*0.50*	*0.50*	
x	0.88	0.63	>	0.00	0.24	<	-0.15	0.16	<
htot	1.13	1.13	=	1.30	1.49	<	1.84	1.66	>
hopt	*2.50*	*2.50*		*2.60*	*2.60*		*3.05*	*3.05*	
Profit	0.42	0.52		1.42	1.46		1.69	2.07	
CS_1	0.38	0.20		0.00	0.02		0.01	0.01	
CS_2	0.02	0.06		0.71	0.71		1.80	1.02	
Welfare	**0.82**	**0.77**	**>**	**2.13**	**2.19**	**<**	**3.50**	**3.11**	**>**

Table 3.2: Numerical results of the three models.

3.7.1 Intuition

The welfare function can be rewritten as a function of the price difference between the countries, the quantity transported, and the total consumption in both countries: $W = f(\Delta p, x, h)$.

The partial derivatives of welfare with respect to these components are the following (Appendix 3.B):

$$\left.\frac{\partial W}{\partial \Delta p}\right|_{x,h} = \rho\ [\Delta c - \Delta p] \tag{3.31}$$

$$\left.\frac{\partial W}{\partial x}\right|_{\Delta p,h} = \begin{cases} \Delta c - t & \text{if } x > 0 \\ \Delta c + t & \text{if } x < 0 \end{cases} \tag{3.32}$$

$$\left.\frac{\partial W}{\partial h}\right|_{x,\Delta p} = \frac{1}{\beta_1 + \beta_2} \left(h_1(c_H) + h_2(c_L) - h\right) \tag{3.33}$$

The subscripts next to the partial derivatives denote which parameters are held constant, while taking the partial derivatives. The welfare optimal levels of Δp, x, and h are found at the point where the partial derivatives are equal to zero:

- The optimal *price difference* Δp is equal to the difference in production costs.

- The optimal amount of *transport* x depends on the transport cost. If $t < \Delta c$, transport should be as large as possible. If $t < \Delta c$, the optimal transport level is zero.

- The optimal *total production* h is equal to $h = h_1(c_H) + h_2(c_L)$. The marginal effect of total production does not depend upon the price difference between the countries.

3.7.2 What drives the welfare effects?

We can now identify the main effects in the three examples (Table 3.2).

Example 1. Total production is not influenced by arbitrage (=, no welfare effect) total transportation increases with arbitrage (>, positive welfare effect) the price difference can be worse or better under arbitrage (?, uncertain welfare effect). The positive welfare effect outweighs the negative welfare effects.

Example 2. Total production is lower with arbitrage (<, negative welfare effect), total transportation decreases with arbitrage (<, negative welfare effect), and lower level of transport), and the price difference is better with arbitrage.(>, positive welfare effect). The negative welfare effects are larger than the positive effects.

Example 3. Total production increases with arbitrage (> , positive welfare effect) total transportation decreases with arbitrage (<, negative welfare effect) the price difference is better under arbitrage (>, positive welfare effect). In total, the positive welfare effects are most important.

3.8 Conclusion

This paper extends the literature on third degree price discrimination. To the standard model it adds costly arbitrage –a constant transportation cost–, and different production costs in each country. It discusses the welfare effects when the monopolist buys the transportation firms, and foreclosures the transportation market.

It is shown that foreclosure is profitable for the monopolist, but often decreases total surplus in the market. However, foreclosure is welfare increasing if the transmission cost is significant but smaller than the cost difference, and demand functions are similar.

The model takes several simplifying assumptions:

Demand functions are linear, and demand can become negative. Negative consumption is explained as competitive fringe. Marginal *production costs* are constant. There are no capacity constraint in production. Also the marginal *transportation costs* are constant, and without capacity constraints.

Extensions

Imposing positive consumption in both regions adds two constraints to the model, but will not change the general results.

With non-linear demand functions, the same solution method can be used.

A companion paper looks at a different supply function for transportation, where transport is costless, but is capacity constrained. It is shown that in that case foreclosure is welfare improving if demand functions are similar, and transmission capacity is small.

An extension to a general upward sloping supply function remains to be studied. Appendix 3.C sets a first step towards such a model.

	Price 1	**Price 2**	**Local optimum when**	
Part 1				
$\tau = t$ and $t < \Delta c$	$p_2 + t$	$\frac{\alpha}{2\beta} + \frac{c_L}{2} - \frac{\beta_1}{2\beta} t$	$x > 0$	(1a) $\chi > -\frac{h_1(c_L)}{\rho} + \left(2 + \frac{\beta_1}{\beta_2}\right) t$
$\tau = t$ and $t > \Delta c$	$\frac{\alpha}{2\beta} + \frac{c_H}{2} + \frac{\beta_2}{2\beta} t$	$p_1 - t$	$x > 0$	(1b) $\chi > \frac{h_2(c_H)}{\rho} + \left(2 + \frac{\beta_2}{\beta_1}\right) t$
Part 2				
$x = 0$	$\frac{\overline{p}_1 + c_H}{2}$	$\frac{\overline{p}_2 + c_L}{2}$	$\Delta p < t$ $\Delta p > -t$	(2) $\chi < -\Delta c + 2t$ (3) $\chi > -\Delta c - 2t$
Part 3				
$\tau = -t$	$p_2 - t$	$\frac{\alpha}{2\beta} + \frac{c_L}{2} + \frac{\beta_1}{2\beta} t$	$x < 0$	(4) $\chi < -\frac{h_1(c_L)}{\rho} - \left(2 + \frac{\beta_1}{\beta_2}\right) t$
Corner A				
$x = 0$ and $\tau = t$	$p_2 + t$	$\frac{\alpha}{2\beta} + \frac{\beta_1 c_H + \beta_2 c_L}{2\beta} - 2\frac{\beta_1}{\beta} t$	$p_2 < \overline{p}_2$	Not (1a,2) if $t < \Delta c$ Not (1b,2) if $t > \Delta c$ (5) $\chi < \frac{h_2(c_L)}{\rho} + 2t - \Delta c$
$x = 0$ and $\tau = t$	$p_2 + t$	$\overline{p}_2$		Not (1a,2,5) if $t < \Delta c$ Not (1b,2,5) if $t > \Delta c$
Corner B				
$x = 0$ and $\tau = -t$	$\frac{\alpha}{2\beta} + \frac{\beta_1 c_H + \beta_2 c_2}{2\beta} - \frac{\beta_2}{\beta} t$	$p_1 + t$	$p_1 < \overline{p}_1$	Not (3,4) (6) $\chi > -\frac{h_1(c_H)}{\rho} - 2t - \Delta c$
$x = 0$ and $\tau = -t$	$\overline{p}_1$	$p_1 + t$		Not (3,4,6)

Table 3.3: Local Equilibria – Arbitrage

Appendix 3.A The local optima with arbitrage

Table 3.3 gives the local optima for the 5 different types of equilibria, and the condition for which they are a valid local equilibrium.

Appendix 3.B Welfare effects

Welfare can be written as a function of $W(p_1, p_2, x)$:

$$W = A + x\Delta c - |x|\, t + p_1\beta_1 c_h - \frac{1}{2}p_1^2\beta_1 + p_2\beta_2 c_L - \frac{1}{2}p_2^2\beta_2$$

with

$$A = \frac{1}{2}\frac{\alpha_1^2}{\beta_1} + \frac{1}{2}\frac{\alpha_2^2}{\beta_2} - \alpha c_L$$

Comparing welfare in part 1, 2, and 3 of the supply function gives the results in Table 3.4.

		Difference in welfare	Welfare Effect
$t < \Delta c$	*Part 1*	$\frac{1}{8}\rho(\chi - t)^2 > 0$	+
	Part 2	$-\frac{3}{8}(\Delta c - t)(2h_1(c_H) + \beta_1(\Delta c - t)) < 0$	−
	Part 3	$\frac{1}{8}\rho\left((\chi + t)^2 + 12\frac{h_1(c_L)}{\rho}t\right) > 0$	+
$t > \Delta c$	*Part 1*	$-\frac{1}{8}\rho\left((\chi - t)^2 - 3\left(\frac{\beta_2}{\rho}(t - \Delta c) + 2\frac{h_1(c_L)}{\rho}\right)(t - \Delta c)\right)$	?
	Part 2	0	=
	Part 3	$\frac{1}{8}\rho\left(3\frac{t + \Delta c}{\rho}(2h_1(c_L) + \beta_1(t - \Delta c)) + (t + \chi)^2\right) > 0$	+

Table 3.4: Comparison of Welfare in the local equilibria.

Appendix 3.C Upward sloping transmission cost

This appendix generalizes the discussion on price discrimination, arbitrage and costly transportation, for general upward sloping transportation cost functions $\tau(x)$.

The first subsection defines the reduced profit function of the monopolist, which is a generalized demand function for transmission.

The next two subsections discuss then the decision to buy transmission capacity with and without arbitrage.

3.C.1 Demand for transmission capacity

Define the reduced profit function of the monopolist $\Pi(x, \Delta p)$. It is the maximal profit a monopolist can obtain, if he owns x rights, and needs to set a price difference Δp between the regions.

$$\Pi(x, \Delta p) = \arg\max_{p_1, p_2} h_1(p_1)(p_1 - c_H) + h_2(p_2)(p_2 - c_L) + x\Delta c \tag{3.34}$$

subject to the positive production constraint and the price difference constraint:

$$h_1(p_1) \geq \quad x \quad (z_1) \tag{3.35}$$

$$h_2(p_2) \geq -x \quad (z_2) \tag{3.36}$$

$$\Delta p = p_1 - p_2 \quad (\lambda) \tag{3.37}$$

The variables between brackets are the Lagrange multipliers: λ is the multiplier of the price difference constraint, z_1 and z_2 are the multipliers of the production constraints.

As the price difference between the countries is fixed, the monopolist has only one degree of freedom left. He can shift the price levels up and down in each country. The monopolist faces the classical trade-off: increasing prices gives him a higher margin, but lowers sales.

The zero production constraint puts an upper bound on the price level in a country: the level of consumption in a country has to be at least the level of import in country i.

The marginal effects of x or Δp on the monopolist's profit are equal to

$$\frac{\partial \Pi(x, \Delta p)}{\partial \Delta p} = \lambda \tag{3.38}$$

$$\frac{\partial \Pi(x, \Delta p)}{\partial x} = \Delta c - z_1 + z_2 \tag{3.39}$$

λ is the marginal valuation of the monopolist for a change in the price difference between the countries. A positive value of λ means the monopolist would prefer a higher price difference Δp. If the monopolist could set the price difference himself, he would set it such that λ becomes zero.

The value of extra transmission is equal to Δc as long as production constraints are not binding. If production constraints are binding, the value of transmission capacity can be higher or lower than Δc.

Linear demand

For linear demand functions the reduced profit function $\Pi(x, \Delta p)$ can be derived. Table 3.5 gives the marginal valuation of the monopolist for transmission capacity x and the price difference Δp. These marginal valuations are the 'demand functions' of the monopolist for transmission and the price difference.

Depending on the level of transmission x, three regions can be considered.

If x is close to zero, the production constraints are not binding. The monopolist produces in both countries. If x is large, there is a lot of import into country 1, and the production constraint in country 1 puts an upper bound on the prices ($z_1 > 0$). The monopolist does no longer produce in country 1, and will only produce in country 2. If x is small, there is a lot of import in country 2, and the production constraint starts to bind in country 2. ($z_2 > 0$). The monopolist only produces in country 1.

Table 3.5 also gives the second order derivatives of the reduced profit function. It shows that both 'demand functions' are downward sloping, *i.e.* the second order derivatives are negative.

$$\frac{\partial^2 \Pi}{\partial \Delta p^2} \leq 0 \tag{3.40}$$

$$\frac{\partial^2 \Pi}{\partial x^2} \leq 0 \tag{3.41}$$

	Small x	**Intermediate x**	**Large x**
	$\eta-\frac{h_2(c_L)}{\rho}-2\frac{x}{\rho}-2\Delta p>0$	$\eta-\frac{h_2(c_L)}{\rho}-2\frac{x}{\rho}-2\Delta p<0$ $\eta+\frac{h_1(c_H)}{\rho}-2\frac{x}{\rho}-2\Delta p>0$	$\eta+\frac{h_1(c_H)}{\rho}-2\frac{x}{\rho}-2\Delta p<0$
$\frac{\partial\Pi}{\partial\Delta p}$	$\frac{\beta_1^2}{\beta_2}\left(\eta-\frac{h_2(c_L)}{\beta_1}-2\frac{x}{\beta_1}-2\Delta p\right)$	$\rho(\eta-2\Delta p)$	$\beta_2\left(\eta+\frac{h_1(c_H)}{\beta_1}-2\frac{x}{\beta_1}-2\Delta p\right)$
$\frac{\partial\Pi}{\partial x}$	$\Delta c+\frac{\beta_1}{\beta_2}\left(\eta-\frac{h_2(c_L)}{\beta_1}-2\frac{x}{\rho}-2\Delta p\right)$	Δc	$\Delta c+\frac{\beta_2}{\beta_1}\left(\eta+\frac{h_1(c_H)}{\rho}-2\frac{x}{\rho}-2\Delta p\right)$
$\frac{\partial^2\Pi}{\partial\Delta p^2}$	$-2\frac{\beta_1^2}{\beta_2}$	-2ρ	$-2\beta_2$
$\frac{\partial^2\Pi}{\partial x^2}$	$-2\frac{\beta_1}{\beta_2}\frac{1}{\rho}$	0	$-2\frac{\beta_2}{\beta_1}\frac{1}{\rho}$
$\frac{\partial^2\Pi}{\partial x\partial\Delta p}$	$-2\frac{\beta_1}{\beta_2}$	0	$-2\frac{\beta_2}{\beta_1}$

$\eta=\chi+\Delta c$

Table 3.5: First and second order derivatives of the reduced profit function.

With linear demand, the reduced profit function Π is concave as the following condition holds:

$$\frac{\partial^2\Pi}{\partial\Delta p^2}\frac{\partial^2\Pi}{\partial x^2}-\left(\frac{\partial\Pi}{\partial x\partial\Delta p}\right)^2\geq 0 \tag{3.42}$$

For non-linear demand functions, it is no longer guaranteed that the reduced profit function is concave.

3.C.2 Arbitrage

The profit of the monopolist is equal the reduced profit function minus the cost for buying transmission capacity:

$$\Pi(\Delta p,x)-x\cdot\tau \tag{3.43}$$

The monopolist chooses the optimal value of Δp, τ and x, subject to the supply function of transport:

$$\tau=\tau(x) \tag{3.44}$$

and the arbitrage condition

$$\Delta p=\tau \tag{3.45}$$

Because of arbitrage, the decision for the transmission capacity x, and setting the price difference Δp are interrelated.

The monopolist chooses his quantity according to the following equation:

$$\underbrace{\tau+\frac{d\tau}{dx}x}_{\text{A}}=\underbrace{\frac{\partial\Pi}{\partial x}}_{\text{B}}+\underbrace{\frac{\partial\Pi}{\partial\Delta p}\frac{d\tau}{dx}}_{\text{C}} \tag{3.46}$$

The term A is the effect on total expenditure on transmission capacity: New transmission rights should be bought (cost is τ). The old transmission rights become more expensive, this cost is $(\frac{d\tau}{dx}x)$.

Term B is the direct impact of obtaining transmission capacity on the profit of the monopolist. It reflects the decrease in production costs as expensive production cost is replaced with low cost production. The marginal effect of this is equal to $\Delta c - z_1 + z_2$.

Term C is the indirect effect of transmission capacity on the profit of the monopolist. Buying more transmission capacity increases the price difference between the regions with a factor $\frac{d\tau}{dx}$. This has an effect on price discrimination between the regions. The marginal effect of a price change is equal to $\frac{\partial \Pi}{\partial \tau} = \lambda$.

Second order conditions

The optimization program of the monopolist has a concave objective function when:

$$\frac{\partial^2 \Pi}{\partial x^2} + 2\frac{\partial^2 \Pi}{\partial x \partial \tau}\tau' + \frac{\partial^2 \Pi}{\partial \tau^2}(\tau')^2 + \frac{\partial \Pi}{\partial \tau}\tau'' - 2\tau' - \tau'' x < 0 \tag{3.47}$$

Assuming the standard downward sloping and concave demand functions, and convex cost functions for transmission this problem does not need to be concave.

However, with a linear demand in each region and a linear supply function for transmission, $\tau = t + \upsilon(x - k)$, the problem is concave. Two special cases of linear supply are the horizontal supply function ($\tau = t, \upsilon = 0$) and the vertical supply function ($x = k,\ \upsilon = \infty$).

The capacity constrained supply function in the previous chapter, and the constant cost transmission cost in this chapter are concave on each segment of the supply function but not on the whole supply function.

3.C.3 No arbitrage

The monopolist chooses $\Delta p, x$, and τ to maximize his profit function

$$\max_{\Delta p, x, \tau} \Pi(\Delta p, x) - x \cdot \tau \tag{3.48}$$

subject to the supply function of transport:

$$\tau = \tau(x) \tag{3.49}$$

As there is no arbitrage, the price difference Δp can be set independently from the transmission price τ.

The first order conditions are the following:

$$\frac{\partial \Pi}{\partial \Delta p} = 0 \tag{3.50}$$

$$\frac{\partial \Pi}{\partial x} = \tau + \frac{d\tau}{dx}x \tag{3.51}$$

The first condition specifies that the price difference is set such that the value of the price difference is equal to zero $\frac{\partial \Pi}{\partial \Delta p} = \lambda = 0$. The second condition imposes that the direct effect of transmission capacity, $\frac{\partial \Pi}{\partial x} = \Delta c - z_1 + z_2$, is equal to the marginal expenditure on transmission capacity.

4

Will an incumbent generator buy import transmission capacity?

A small region has a high cost monopolistic electricity generator. It is connected through a low capacity transmission line with a large, competitive low cost region. Access to the transmission line is auctioned. I show that the monopolist has a higher valuation for transmission than arbitrageurs. If all transmission is sold in one package, the monopolist will buy it. If transmission is allocated in a first price auction to very small arbitrageurs, then the monopolist will buy no capacity.

4.1 Introduction

The paper tries to give some simple intuition for what happens when an incumbent monopolist is allowed to buy import capacity. The results in this paper are not new (see for instance Joskow and Tirole, 2000), but are presented in a simpler way.

We consider the standard two node network, with a monopoly in the importing region, and a competitive market in the exporting region. Access to the transmission line is auctioned. We study whether arbitrageurs or the monopolist will buy the transmission capacity.

The model has been inspired by the situation at the French-Belgian border. France has cheap nuclear power. Given the small transmission capacity of the lines between France and Belgium, the interconnecting transmission lines are almost always congested. Belgian consumers are concerned that the Belgian incumbent generator will buy all transmission capacity to keep out his competitors. We show under which conditions this will be the case. Note that the paper assumes that the French electricity market is competitive, which is contrary to what most people think.

In the introduction (Chapter 1) it has been shown that in a one-stage game with perfect arbitrage the monopolist is indifferent who buys the transmission capacity, he or the arbitrageurs (*The equivalence theorem*). This chapter uses a two-stage game. In stage one, the arbitrageurs and the monopolist buy transmission capacity. In stage two the monopolist sets the prices. It is shown that the monopolist has a higher valuation for transmission capacity than the arbitrageurs. Owning transmission capacity gives the monopolist not only the possibility to import cheap electricity, but also increases his market power in his home market. The timing of the game introduces a strategic aspect in the game.

It depends on the structure of the model, who will buy the transmission rights in stage one. If all transmission capacity is allocated in one block, then the monopolist buys all transmission capacity. If transmission is allocated in a first price auction to very small arbitrageurs, then the monopolist will buy no capacity.

4.2 Set up of the model

Consider two regions $i \in \{1, 2\}$ (Figure 4.1). Region 1 has consumers with a demand for electricity $h(p)$, and a monopolistic generator with a constant marginal production cost c_H. Region 2 has a competitive electricity market with a constant marginal production cost c_L. Production costs are higher in region 1 than in region 2.($\Delta c = c_H - c_L > 0$). As region 2 is competitive, its price for electricity is c_L.

A transmission line with limited capacity k connects both regions.

The model has two stages:

In *the first stage*, the monopolist buys x_G transmission rights, and the arbitrageurs buy x_A rights. It is assumed that transmission capacity k is small, so that the transmission constraint is always binding $k = x_A + x_G$.

In *the second stage*, the monopolist sets the price for electricity given the amount of transmission rights that were sold (x_G and $x_A = k - x_G$). He maximizes his profit function

$$\pi(p, x_G) = h(p)(p - c_H) - x_A(p - c_H) + x_G \,\Delta c \qquad (4.1)$$

The profit function has three terms. The first term is the monopolist's profit when there would be no transport at all. He produces all electricity locally at a cost c_H, and sells $h(p)$ units of electricity at a price p. The second term is the sales lost to arbitrageurs who import x_A. The third term, x_G, is cost reduction for the monopolist who can buy electricity at a lower price.

As it has been assumed that $x_A = k - x_G$, the objective function of the monopolist can be written as a function of p, and x_G only.

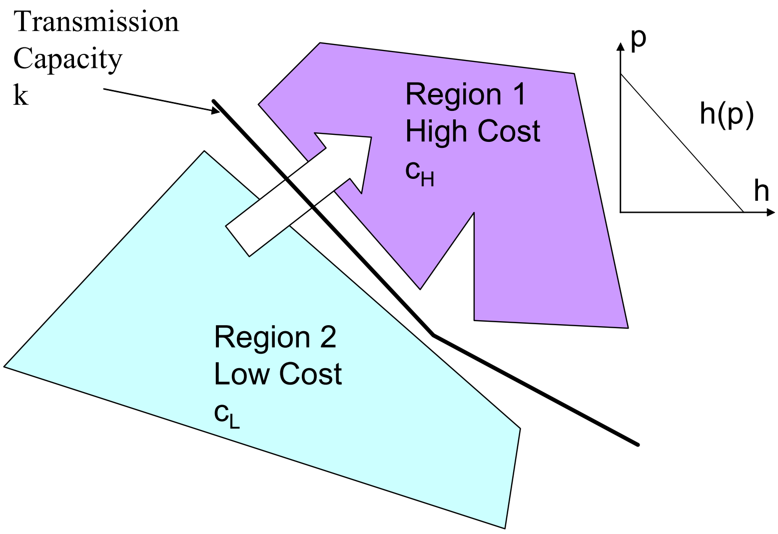

Figure 4.1: The model considers two regions, region 1 has a high cost monopolist, and region 2 has a low cost perfectly competitive market. Consumers in region 1 have a demand function $h(p)$.

4.3 All capacity is sold at once

In this section we assume that all transmission capacity is sold in one package: *i.e.* either the consumers or the monopolist end up with all the transmission rights. We solve the model first for the second stage.

Second stage We compare the two possible allocations: (1) Arbitrageurs have all the transmission rights ($x_G = 0$, and $x_A = k$), and (2) The monopolist has the transmission rights. ($x_G = k$, and $x_A = 0$).

If *arbitrageurs* own the rights (Figure 4.2), then the monopolist has a residual demand function $h(p) - k$ and obtains a profit:

$$\pi(p, 0) = (p - c_H)(h(p) - k) \tag{4.2}$$

He sets a price $p(0) = \arg\max_p \pi(p, 0)$. In Figure 4.2 the monopolist obtains a profit $B = \pi(p(0), 0)$.

If the *monopolist* owns the rights, he obtains a profit

$$\pi(p, k) = (p - c_H)\ h(p) + \Delta c\ k \tag{4.3}$$

He maximizes against the full demand function and receives a profit $k\ \Delta c$ from importing cheap electricity (Figure 4.3). He sets the price $p(k)\ = \arg\max_p \pi(p, k)$. In Figure 4.3 the profit of the monopolist is the area B'.

First Stage In stage 1, the players bid for the transmission rights. Without specifying the actual mechanism we assume that the player with the highest

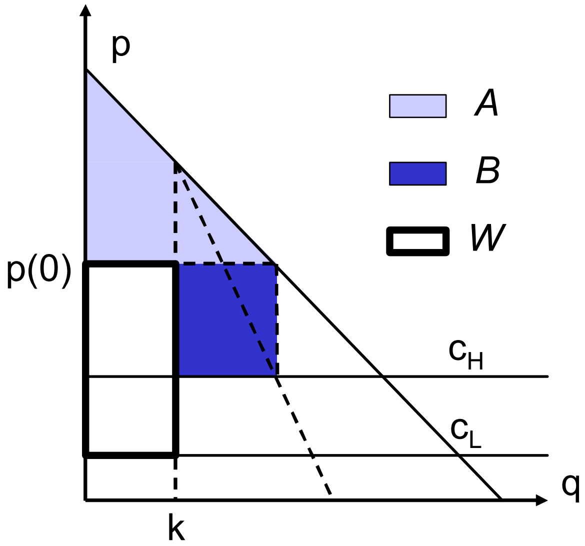

Figure 4.2: Arbitrageurs own the transmission capacity. The optimal price for the monopolist is $p(0)$. The area B is the monopoly profit, area A the consumers surplus, and area W the value of the transmission rights for the arbitrageurs.

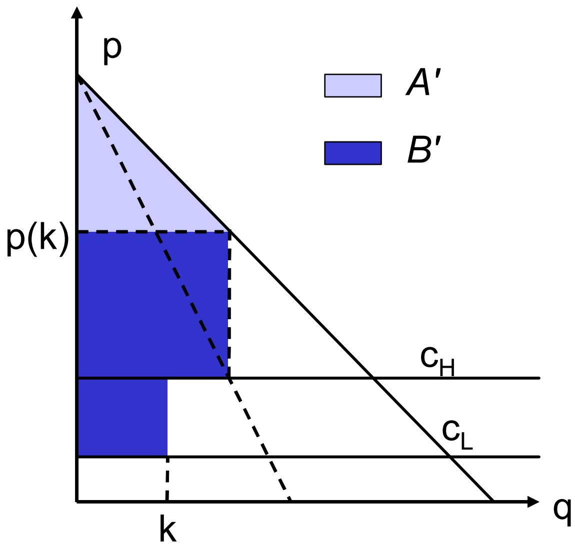

Figure 4.3: The monopolist owns the transmission capacity. The optimal price for the monopolist is p^M. The area B' is the monopoly profit. Area A' the consumers surplus.

valuation receives the transmission rights. As there is perfect information in the game, this is what happens for the standard auctions. The value of owning the transmission right for the monopolist is

$$V = \pi(p(k), k) - \pi(p(0), 0) \tag{4.4}$$

In the figures this is area $B' - B$.

The value for arbitrageurs of a unit of transmission rights is equal to the price difference between the regions: $p(0) - c_L$. Their total valuation for k transmission rights is

$$W = (p(0) - c_L)k. \tag{4.5}$$

See region W in Figure 4.2.

The monopolist has a higher valuation than the consumers

$$V > W \tag{4.6}$$

The proof is simple and uses a revealed preference argument for the monopolist. It is obvious that $B + W < B'$, as otherwise $p(k)$ would not be the optimal price for the monopolist. Rearranging the terms gives $W < B' - B$, which is equation 4.6.

Welfare is higher if arbitrageurs obtain all the transmission capacity.[1]

$$A + B + W > A' + B' \tag{4.7}$$

Therefore it is optimal to forbid the monopolist to buy the transmission rights.

Note: If arbitrageurs and consumers can coordinate, they would organize themselves and take into account the infra-marginal rents. Their valuation for transmission rights is now equal to:

$$W^* = U(p(0)) + k(p(0) - c_L) - U(p(k)) \tag{4.8}$$

with $U(p) = \int_p^{\bar{p}} q(t)dt$, the net consumer surplus, and $\bar{p}$ the reservation price. It is the difference of the consumers surplus in both allocations. In the figures $W^* = A + W - A'$. Consumers and arbitrageurs together have a higher valuation than the monopolist.

$$V < W^* \tag{4.9}$$

The proof follows directly from the fact that welfare is higher if transmission rights are allocated to consumers. $(A + B + W > A' + B')$. Rearranging the terms implies that $B' - B < A + W - A'$ which is precisely equation 4.9.

[1] Equation 4.7 is always true. Equation 4.6 is less general, but will be true when the demand functions are concave.

4.3.1 Relation with the literature

The intuition in this paper is closely related to the literature on the sales of operating licenses (Borenstein, 1988), or the value of a patent for an incumbent vs. an entrant. (Gilbert and Newbery 1982, 1984).

The main insight from this literature is that the value that a player assigns for obtaining a right, patent or license is not perfectly correlated with the social value of allocating that right to that player.

In the R&D literature, one typically describes two aspects that influence the valuation of the monopolist:

On the one hand the monopolist values a patent less than the social value, as he has an output which is lower than the social optimum. Therefore the benefit of an invention is spread over a smaller number of goods. This aspect is called the *replacement effect.* (Arrow, 1962). In this chapter, this effect does not play a role, as it is assumed that the transmission right has only a small capacity. If transmission capacity would be large, the replacement effect would play a role.

On the other hand, if there is competition, the monopolist might lose part of his monopoly profit to an entrant. Therefore, his valuation of the right might be higher than the value of a competitor. This effect is called the *efficiency effect.* This effect dominates in this chapter. The monopolist has a higher value for the transmission rights than the arbitrageurs as it not only increases his efficiency, but also allows him to keep his monopoly position.

In the R&D literature this means that the monopolist overinvests in research. Here the monopolist pays too much for the rights.

4.4 Continuous allocation

In this section we assume that transmission capacity is sold in a first price auction, and that bids are possible for infinitesimal parts of the capacity.

Second Stage The monopolist obtained x_G transmission rights in the first period. The monopolist maximizes profit and sets a price

$$p(x_G) = \arg\max_p \pi(p, x_G) \tag{4.10}$$

If the monopolist owns more transmission rights, his market power increases and he will set a higher electricity price:[2]

$$\frac{dp(x_G)}{dx_G} > 0 \tag{4.11}$$

[2]This follows from $p'(k^M) = -\frac{\pi_{pk}}{\pi_{pp}}$, which is positive if the demand is concave. and $p > c_H$. The latter is always the case for small transmission capacities, such that there remains local production. Gilbert *et al.* show this is still valid in an oligopoly setting, under a wide range of assumptions.

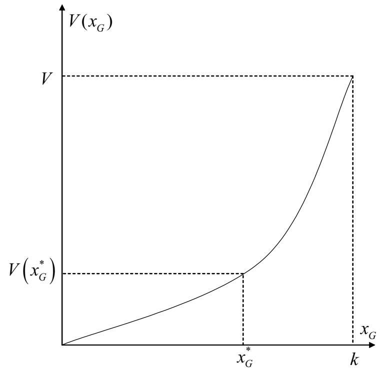

Figure 4.4: Normalized profit function $V(x_G)$ of the monopolist.

The actions of the monopolist in the first period depend only on the normalized profit function $V(x_G)$ of the monopolist (Figure 4.4):

$$V(x_G) = \pi(p(x_G), x_G) - \pi(p(0), 0) \tag{4.12}$$

The function $V(x_G)$ is the generalization of the value of all transmission rights in the previous section. There we looked at two corner points of the allocation: $x_G = 0$ and $x_G = k$: If the monopolist owns all the transmission capacity, his normalized profit is equal to $V(k) = V$. If he has no transmission capacity he gets zero profit $V(0) = 0$.

The inverse demand function of the monopolist for transmission is his marginal willingness to pay. It can be calculated using the envelope theorem:

$$\frac{dV(x_G)}{dx_G} = \frac{\partial \pi(p, x_G)}{\partial x_G} = p(x_G) - c_L \tag{4.13}$$

His marginal valuation is equal to the regional price difference.[3] The inverse demand function for transmission is thus an *increasing (!)* function in the transmission capacity. See Figure 4.5.

For an arbitrageur, the value of one unit of transmission capacity is equal to the regional price difference. $(p(x_G) - c_L)$. The full line in Figure 4.7, presents the valuation of one unit of transmission capacity, when other arbitrageurs have x_A transmission rights. Note that his valuation is equal to the marginal valuation of the monopolist.

If all arbitrageurs together own x_A transmission rights, their total value is equal to: $W(x_A) = (p(x_G) - c_L)\ x_A$ (Figure 4.6). If the arbitrageurs own no transmission capacity, their value is equal to $W(0) = 0$. If the arbitrageurs own all the transmission capacity, their value is $W(k) = W$. These two points were the corners solutions in the previous section.

[3]Gilbert *et al.* show that in a Cournot case the marginal valuation of a player is below the price difference. (Proposition 1 of their paper). The reason for this is that owning transmission rights has an effect on the behavior of other players as well. Therefore there is an extra negative term in equation 4.13 if the envelope theorem is applied.

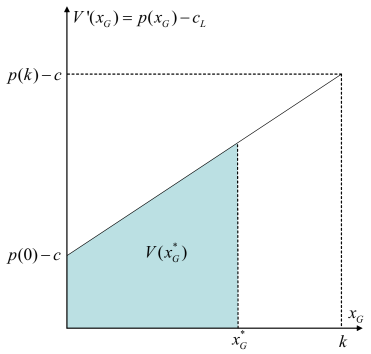

Figure 4.5: The monopolist's demand function for transmission capacity.

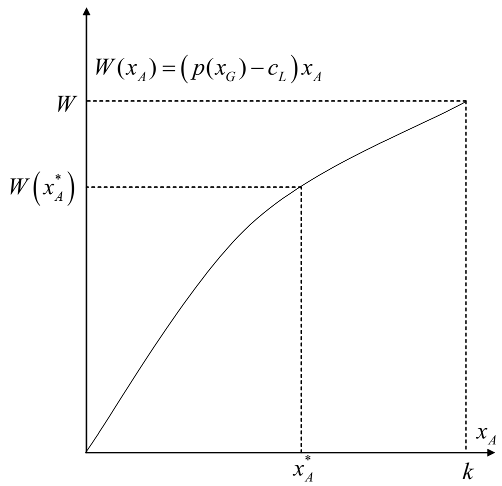

Figure 4.6: Value of transmission capacity for all arbitrageurs together. $(W(x_A))$

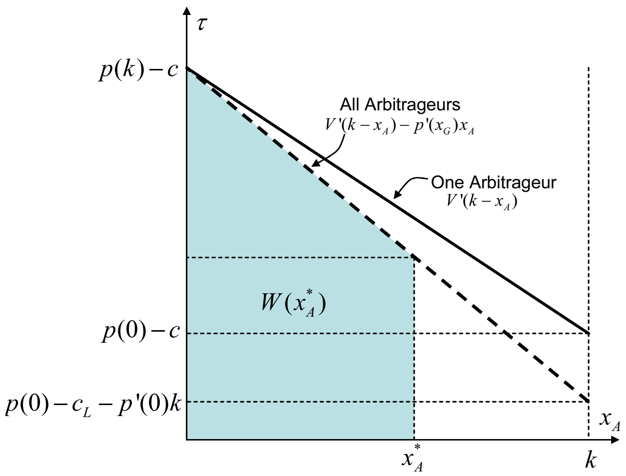

Figure 4.7: Demand by one arbitrageur, and all arbitrageurs acting together.

The inverse demand function of the arbitrageurs for transmission rights is equal to

$$\frac{\partial W(x_A)}{\partial x_A} = p(x_G) - c_L \; - p'(x_G)\, x_A. \tag{4.14}$$

The demand for transmission *decreases* if the price increases (See the dotted line in Figure 4.7).

Figure 4.8 combines the information of figures 4.5 and 4.7. This is done by changing the direction of the X-axis in Figure 4.7, and using the fact that $x_A = k - x_G$.

Reading Figure 4.8 from left to right, the full line is the demand function of the monopolist. Reading Figure 4.8 from right to left, the dotted line is the demand function of all arbitrageurs acting together.

If the monopolist owns x_G^* transmission rights, his normalized profit is $V(x_G^*)$. If arbitrageurs own x_A^* transmission rights, their profit is $W(x_A^*)$.

The figures show clearly that the marginal valuation of transmission is lower for the arbitrageurs together than for the monopolist. This can be seen numerically by comparing equation 4.13 and 4.14.

The figure also confirms the results of the previous section. Allocating all capacity to the monopolist gives him a profit V, (the area $acfg$ in Figure 4.8). Allocating all transmission capacity to the arbitrageurs, gives them a profit W (the area $abfg$). The value for the arbitrageurs W is lower than the value for the monopolist V.

First stage In the first stage, the arbitrageurs and the monopolist bid for transmission capacity in a first price auction.[4] We will assume that there is a

[4]This is similar to the model of Gilbert *et al.* In Joskow and Tirole, the arbitrageurs already own the transmission capacity, and have to decide if they will sell it to the mo-

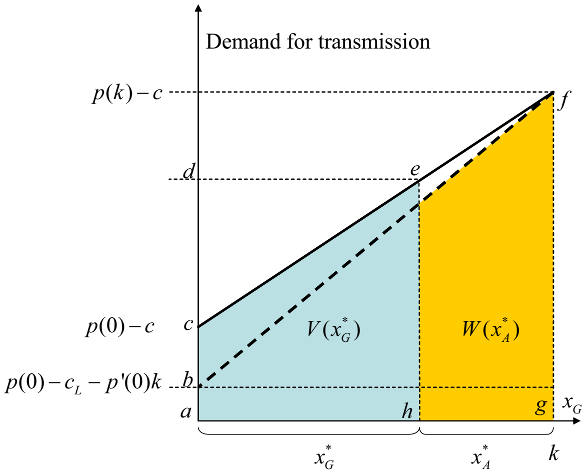

Figure 4.8: Demand by the monopolist and the arbitrageurs.

continuum of very small arbitrageurs $y \in [0, k]$. Each consumer submits a bid $b(y)$ in order to obtain an infinitesimal small amount of transmission capacity dy. The aggregate bid of the arbitrageurs is the aggregation of all individual bids, into an aggregate bid function $\tau(x_A)$. Total demand for transmission by the arbitrageurs at a price p is equal to the number of bidders who did bid more than the price p:

$$\tau^{-1}(p) = \int_0^k \mathbf{1}_{\{b(y)>p\}} dy \tag{4.15}$$

With **1** the indicator function.[5]

The monopolist bids an increasing bid function $f : [0, k] \to \mathrm{R} : x_G \to f(x_G)$. For x_G transmission rights, he is willing to pay $f(x_G) \cdot x_G$.

Proposition 6. *Suppose that the arbitrageurs bid $b(y) = p(y) - c$, and the monopolist bids a fixed price $f(x_G) = M^* \in [0, p(0) - c[$, then this is a Nash equilibrium, and the monopolist buys no transmission rights.*[6]

Proof: The aggregate bid function of the arbitrageurs is equal to $\tau(x_A) = (p(k - x_A) - c)$. Given the strategies of the players, the arbitrageurs obtain all the transmission capacity $(x_A = k)$ at a price $(p(0) - c)$. As they all make zero profit, deviating cannot increase profits.

Also the monopolist makes zero profit. Deviating from his strategy is not profitable. If the monopolist buys x_G^* transmission rights he obtains the

nopolist. Here, the initial owner of the rights is the network operator who sells the rights to arbitrageurs and the monopolist.

[5]The indicator function is equal to one, when the condition is satisfied, and zero when not.

[6]This repeats some of the arguments in Joskow and Tirole, and of Gilbert *et al.*.

profit $V(x_G^*)$ in Figure 4.8. But he will have to pay $(p(x_G) - c)x_G$ (area *adeh*), which is more than the value of the rights. Therefore, the monopolist prefers not to buy transmission capacity.

Discussion. The first price auction ensures that the monopolist pays in the first period a transmission price τ that is equal to the price difference in the second period $\tau = p(x_G) - c_H$. Instead of looking for the Nash equilibrium of the arbitrageurs, we could also have imposed that there is perfect arbitrage in the first period.

The price that the monopolist has to pay is equal to the marginal value of the rights. As the marginal value of the rights is increasing, he does not buy any transmission rights, because they are too expensive for him.[7]

4.5 Conclusion

The paper considers a small, high cost, monopolistic region, that imports electricity from a large, low cost, competitive region. Import capacity is limited by transmission constraints, and transmission capacity is auctioned to arbitrageurs and to the monopolist.

We show that the monopolist has a higher valuation for transmission capacity than the arbitrageurs. The reason is that transmission rights help him setting a higher price for electricity.

Therefore, if the transmission rights would be sold in a single package, the monopolist would buy it. Forbidding the monopolist to buy importing capacity, leads to lower electricity prices and is welfare improving.

However, as shown by Joskow and Tirole (2000), it is very difficult to generalize these conclusions in a meshed network with variable demand, when transmission rights are also used to hedge uncertainties.

In the second part of the paper, we do not longer assume that transmission rights are sold in a package. Instead, we assume a first price auction for transmission rights, and a large number of small arbitrageurs. Under these assumptions, arbitrage is perfect: the monopolist pays a transmission price τ equal to the price difference between the regions.

Under perfect arbitrage, the monopolist does not buy any transmission rights. This follows from the fact that his demand for transmission is increasing in its price, and that perfect arbitrage obliges him to pay his marginal valuation. So, despite the higher value of transmission rights for the monopolist, perfect arbitrage prevents the monopolist from buying transmission rights.

[7] Joskow & Tirole showed the analogy with the literature on takeovers (Grossman and Hart, 1980).

Cournot players have a lower marginal value for transmission rights than the monopolist. (see Gilbert at al.). Therefore, they would like to buy a negative quantity of transmission contracts, *i.e.* they sell transmission rights.

How robust is the conclusion that he will not buy transmission rights? Some comments:

1. We only looked at one equilibrium in the transmission market, there could be other Nash equilibria where the monopolist obtains some of the transmission rights.

2. If the monopolist is allowed to make a bid conditional on obtaining all transmission capacity, he will end up with all transmission capacity. It is sufficient that he is allowed to make his total payments a convex bid in function of the rights he obtains $T(x_G)$. In the case above, he was obliged to make prices linear. $T(x_G) = f(x_G) \cdot x_G$.

3. If the monopolist could commit himself to set a low price for electricity if he does not obtain all the transmission rights, he can deter arbitrageurs of buying transmission rights.

4. If each arbitrageur has to buy a minimum amount of capacity, the results of the first price auction become more like the one where everything is sold in one package. There will no longer be perfect arbitrage, and the monopolist will buy some of the transmission capacity.

5. The results depend strongly on the assumption of having a first price auction. In appendix 4.B, we look at a pay-as-bid auction, and show that there is no longer perfect arbitrage.

$$\tau < p(x_G) - c_H \tag{4.16}$$

   Now, the monopolist receives transmission capacity with a positive probability. The revenue for the network operator is higher than in the first price auction, and expected welfare is lower.

6. In general, if the auctioneer is profit maximizing, he would like to use a mechanism that allocates the transmission rights to the player with the highest valuation, *i.e.* the monopolist.

Appendix 4.A Extension of the model

This appendix links this chapter with the previous chapters in the thesis.

First it rewrites the model in the notation of Appendix 3.C. Then it shows that the one-stage model with arbitrage and the two-stage model with arbitrage are equivalent *i.e.* equivalence between Chapter 4 and Chapter 2 Finally, it gives an alternative 'proof' that the arbitrageurs buy all transmission capacity in stage one.

Rewriting the model Recall the notation from Chapter 3. There are two countries 1 and 2, with demand function $h_i(p_i)$, and production costs c_H and c_L for the monopolist. The price difference and the production cost difference are $\Delta p = p_1 - p_2$, and $\Delta c = c_H - c_L$ Arbitrageurs and the monopolist use transport capacity x_A and x_G. In total $x = x_A + x_G$ units of electricity are transported. The supply function for transmission is $\tau(x)$. The profit of the monopolist can be written as:

$$\Pi(\Delta p, x) - x_A \Delta p - x_G \tau + x \Delta c \tag{4.17}$$

where $\Pi(\Delta p, x)$ is the reduced profit function of the monopolist (3.C).

The model in this chapter has two stages. In the second stage, the monopolist sets the price difference Δp between the regions. In the first stage the monopolist buys transmission capacity.

Second stage The monopolist maximizes his profit with respect to the price difference Δp, keeping x_G and x_A fixed. He sets Δp such that

$$\Pi_{\Delta p}(\Delta p, x) = x_A \tag{4.18}$$

This is the first order condition of profit function 4.17 with respect to the price difference Δp. It is the *incentive constraint*, and specifies the behavior of the monopolist in the second stage.

First Stage Above it has been shown that the monopolist faces perfect arbitrage:

$$\tau = \Delta p \tag{4.19}$$

when transmission is sold in a first price auction, and when there are a large number of small arbitrageurs.

The monopolist maximizes his profit, by setting x_A and x_G

$$\Pi(\Delta p, x) - x_A(\Delta p - \Delta c) - x_G(\tau - \Delta c) \tag{4.20}$$

subject to the following constraints

$$\Pi_{\Delta p}(\Delta p, x) = x_A \tag{4.21}$$

$$\tau = \tau(x) \tag{4.22}$$

$$\tau = \Delta p \tag{4.23}$$

The first constraint is the *incentive constraint* in the second stage, the second condition is the supply function of transmission, and the last constraint is the arbitrage condition of the arbitrageurs.

The arbitrage constraint can be substituted in the objective function, after which the problem of the monopolist becomes:

$$\max_{\tau, x, x_A} \Pi(\tau, x) - x(\tau - \Delta c) \tag{4.24}$$

subject to

$$\Pi_\tau = x_A \tag{4.25}$$
$$\tau = \tau(x) \tag{4.26}$$

The first constraint is the only equation in which x_A appears. The constraint has therefore no impact on the optimization problem, *i.e.* the Lagrange multiplier of this constraint is zero. Depending on the form of the transmission cost function the problem reduces to that in Chapter 3 or Chapter 4. This proves the following proposition:

Proposition 7. *A two-stage game where transmission is sold in a first price auction, is equivalent with a one-stage game with perfect arbitrage.*

This conclusion is valid both in the short-run as in the long-run.

Intuition

The only difference between the first stage of the two stage game and the one-stage game is that the incentive constraint (of the second stage) is added to the optimization problem. The incentive constraint depends on the specific distribution of x_C and x_G. The monopolist will be more or less aggressive in the second stage, depending on the number of rights he and the arbitrageurs have. All other constraints, and also the objective function depend only on x and not on x_G and x_A separately. There is thus one degree of freedom left to adjust the incentive constraint until it is no longer binding.

Extension: Oligopoly

Neuhoff (2003) compares Chapter 2 and Chapter 4 in an oligopoly setting. Now, the equivalence result does not hold. A one stage game (Chapter 2) is more competitive than a two stage game (Chapter 4). The reason for this is that in a one stage game, the residual demand functions for the oligopolists are more elastic than in the second stage of the two-stage game.

The arbitrageurs buy all capacity We will now use the new formulation to give an alternative proof that the monopolist does not buy transmission capacity. As above, assume that transmission capacity is small, so that there is always congestion.

In the formulation of this appendix that means that the supply 'function' $\tau(x)$ is a vertical line with $x = k$ on which τ can be chosen freely.

Rewriting the program in equation 4.24 with the new supply function gives

$$\max_{\tau, x_A} \Pi(\tau, k) - k(\tau - \Delta c) \tag{4.27}$$

subject to the *incentive constraint:*

$$\Pi_\tau(\tau, k) = x_A \tag{4.28}$$

The first order condition with respect to τ gives the optimal transmission price:

$$\Pi_{\tau}(\tau, k) = k \tag{4.29}$$

Comparing this condition with the incentive constraint, shows that the arbitrageurs buy all transmission:

$$x_A = k \tag{4.30}$$

Appendix 4.B Pay-as-bid auction

This appendix replaces the first price auction with a pay-as-bid auction. It shows that there is no longer perfect arbitrage in the first stage.

A pure strategy equilibrium does not exist in the pay-as-bid auction. Therefore we look for a mixed strategy equilibrium.[8]

The monopolist submits a random bid τ for all transmission capacity. The cumulative distribution of his bid is $H(\tau)$.

Arbitrageurs make the monopolist indifferent between obtaining x_G rights and obtaining no rights. If the monopolist obtains no rights his profit is equal to $V(0) = 0$. If the monopolist obtains x_G rights, he should also obtain a zero profit. Otherwise, he would not be indifferent between the two cases. The price that the monopolist pays for x_G rights is thus equal to the average value:

$$\tau = v(x_G) \tag{4.31}$$

with $v(x_G) = \frac{V(x_G)}{x_G}$.

The aggregate bid function of the arbitrageurs with the pay-as-bid auction ($\tau^{PAB}(X_A)$) is thus:

$$\tau^{PAB}(x_A) = v(k - x_A) \tag{4.32}$$

The dotted line in Figure 4.9 presents the aggregate bid function. It is easy to show that the average value of transmission capacity is smaller than the marginal value of transmission capacity.

$$V'(x_G) \geq v(x_G) \tag{4.33}$$

Above it was shown that the marginal value of transmission capacity is equal to the regional price difference (see the full line in Figure 4.9.)

$$V'(x_G) = p(x_G) - c_L \tag{4.34}$$

It follows that the monopolist pays less than the regional price difference. Arbitrage is thus no longer perfect.

[8] The solution is inspired by Gilbert *et al.* but the results are generalized for non-linear demand functions.

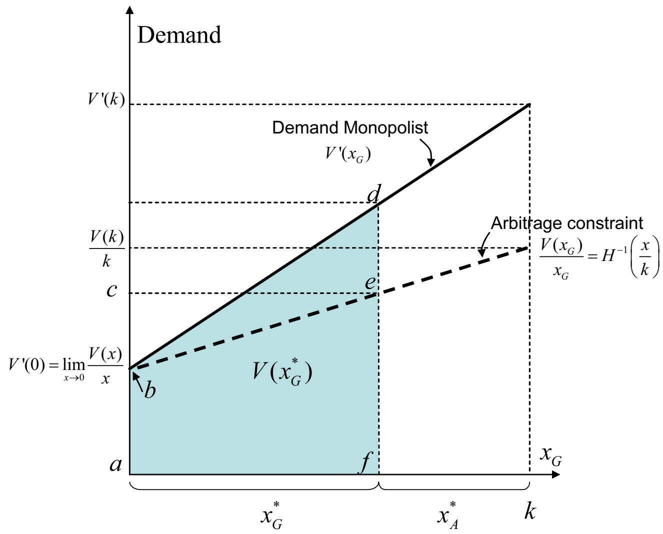

Figure 4.9: Aggregate bid function of the arbitrageurs, and the marginal value of the monopolist in the pay-as-bid auction.

The cumulative distribution function of the monopolist is such that each arbitrageur gets zero profit in expectation. It can be shown that the cumulative distribution function of the monopolist is given by

$$H(\tau) = \frac{v^{-1}(\tau)}{k} \tag{4.35}$$

for $\tau \in [v(0), v(k)]$

Let us now compare the pay-as-bid auction with the first price auction.

With the pay-as-bid auction there is *no longer perfect arbitrage* in the first stage of the game. The monopolist pays a transmission price τ which is smaller than the regional price difference.

$$\tau < \Delta p \tag{4.36}$$

The monopolist obtains transmission rights with a positive probability. His market power increases, and as a result he sets higher prices for electricity. This *decreases welfare* .

The monopolist and the arbitrageurs obtain zero profit under both auction types, so they are both indifferent between the two.

The network operator receives in expectation a higher income from selling the transmission rights under the pay-as-bid auction. Before his income was $v(0)\ k$. Now the expected level of income is equal to $\int_0^k v(x)dx$. The *network operator prefers the pay-as-bid auction.*

Note:

Gilbert *et al.* look at the pay-as-bid auction in an oligopoly setting with linear demand. In an oligopoly setting the generators will obtain rights with a certain probability which enhances their market power.[9]

[9] Proposition 7 in their paper.

Part II

Cournot model with Rationing

5

Modeling Cournot Competition in an Electricity Market with Transmission Constraints.

This paper studies Cournot competition with two generators who share one transmission line with a limited capacity to supply price-taking consumers. In such a game the network operator needs a rule to allocate transmission capacity. We study three rules: all-or-nothing, proportional, and efficient rationing. The first result is that if the network operator taxes the whole congestion rent, the generators strategically change their production quantities, such that the network operator obtains no congestion rent. This gives poor incentives for investment in transmission capacity. The second result is that the network operator can create competition among the generators, which can increase welfare. Marginal nodal congestion pricing, which is optimal under perfect competition, is sub-optimal when generators can set their production quantities freely. It does not generate revenue for the network operator, nor does it increase competition among the generators.

5.1 Introduction

Many countries are currently liberalizing their electricity industries. To enhance competition, most countries separate the transmission sector from the generation sector. The transmission network not only transports electricity from where it is produced to where it is consumed, but also promotes market efficiency as it allows several generators to compete for the same consumers.

However, the capacity of transmission lines is limited by technical constraints. It cannot be extended easily because the construction of transmission lines takes a long time, and there is a strong opposition by environmentalists. Therefore, the opening of the electricity market will be limited by transmission capacity in the next ten to fifteen years. In this paper we study imperfect competition in generation in the presence of transmission constraints.

We discuss the case in which two generators are located on one end of a transmission line and are providing electricity to a set of price taking consumers at the other end of the line. Transport over this transmission line is costless.

Oren (1997) studies this problem using a Cournot model. He argues that the generators obtain all the congestion rent of the transmission line, independent of the number of generators that compete for the use of the line. This model has been criticized by Stoft (1999), because it uses a non-standard equilibrium concept. In this paper we show that by reformulating Oren's model, the same outcome is obtained using the Nash equilibrium concept. In order to do so, the role of the network operator has to be made explicit. This network operator taxes all the rent of both generators as soon as there is congestion. The generators make zero profit when they create congestion, and hence avoid doing so. As a result, the network operator receives no congestion payments.

The second result of the paper is that if generators are located at the same end of the transmission line, the market for electricity may become more competitive with the capacity constrained transmission line than without. This increased competition may increase welfare. The underlying reason is that the network operator has more bargaining power than the consumers, who are assumed to be price takers. He can organize competition for the transmission capacity. To do this, the network operator rewards players for bidding more aggressively. In our second model, the network operator allocates the transmission capacity proportionally to the bids if there is congestion. Generators bid more aggressively for the transmission capacity, because this reduces the capacity available for their competitor. This reward for bidding aggressively is not present in standard congestion pricing, where all congestion is taxed, and no reward is left to the players.

This result contrasts nicely with the model of Borenstein *et al.* (1998) where the generators are located on different ends of the transmission line. In this model the limited transmission capacity makes the market less competitive. The generators reduce their own bids in order to reduce the transmission capacity available for the other player.

The role of the network operator is thus crucial to *creating competition* among the generators, and *extracting the congestion rent from the generators.*

In a third model we look at a naïve implementation of marginal nodal pricing. The entire rent of the least efficient generator is taxed if there is congestion, whereas transmission is not taxed if there is no congestion. This implementation scores badly on both points, because it does not take the strategies of the generators into account.

In the social optimum, the network operator should act more aggressively, so that the generators cannot evade taxation.

5.1.1 Overview of the paper

The next section reviews the literature. Section 3 presents the set-up of the model and derives the standard Cournot equilibrium when there are no transmission constraints. The next two sections form the core of the paper and discuss Cournot competition in a setting with limited transmission capacity. The major problem in such a model is that the total transmission capacity demanded by the generators may exceed supply. Oren suggests solving this problem via a Generalized Nash Equilibrium. In such an equilibrium the generators 'internalize' the external transmission constraint. This is explained in section 4. But this is not standard. We solve this problem via a Nash Equilibrium. Section 5 assumes that the network operator uses a rationing rule when demand for transmission capacity exceeds supply. Section 6 addresses an optimal contract in the same framework. Section 7 concludes the paper.

5.2 Literature Review

We start with a short description of transmission pricing under perfect competition. Then we see how one player strategically sets his production to get a higher profit. The role of congestion rent is highlighted. A classification of the influence of the transmission network on competition follows. The last part of the review describes the different market structures and the applicability of our model.

5.2.1 Perfect Competition

Under perfect competition, transmission is priced at its opportunity cost; this is called *nodal spot pricing.* (Schweppe *et al.* 1988) Nodal spot pricing ensures that, given the constraints of the network, generation and consumption are scheduled efficiently. (*short-run efficiency*).

The transmission charge paid by the generators is the *congestion rent.* This congestion rent can be used to reward investors who invest in transmission capacity. These congestion payments also make sure that investment in generation occurs at the right location in the network. (*long-run efficiency*) Optimal nodal pricing results in both short-run and long-run efficiency, giving the right signals for short-run production decisions and for investment in transmission and generation capacity.

5.2.2 Strategic action of one generator

If one generator is not behaving as a price taker, we no longer have perfect competition. Such a generator sets his power production taking into account the effect of his decision on the electricity price and on the level of congestion in the network. Because the perfect competitive equilibrium maximizes total surplus, the only way to increase profit above the competitive level is to capture part of the rent of the other players. Joskow and Tirole (2000) show that in a network with nodal pricing there are three categories of players from whom he can obtain rent: the consumers, the other generators and the network operator. He can obtain part of the consumers' surplus by reducing their consumption and thus increasing the price they have to pay (monopoly behavior). The surplus of the competitive fringe generators can be obtained by reducing their production, and with an upward sloping marginal cost function they receive a lower price for their electricity (monopsony behavior). This reduction is possible by creating congestion that 'obstructs' the production of these generators. Both these actions create a deadweight loss and decrease short-run production efficiency. In addition, this strategic player can also extract rent from the network operator. The network operator receives the congestion payments of the players. By influencing the level of congestion these payments can be reduced. In the short-run this is a pure transfer from the network operator to the strategic player, but in the long-run this has high efficiency costs:

- If generators upstream of a congested link appropriate more rent than under a perfectly competitive market, too many generators enter the market, with a wasted replication of fixed investments.
- The appropriation of the congestion rent by the generators can reduce investment incentives in transmission capacity. The question of who obtains the congestion rent forms an important issue in this paper.

5.2.3 Strategic effects of transmission lines

The strategic effects, although derived for one strategic player, are still valid when there are several strategic players. But now, each player takes into account the strategic effects of his action on the actions of the other players.

Transmission constraints influence strategic interaction in two ways: by splitting the market into two sub markets, and by the creation of competition for scarce transmission capacity. These two effects can be recognized in a model with only one transmission line and two generators.

Positive externality When we place the generators on different ends of the line, transmission of electricity creates a positive externality[1] for the generators. A generator transporting electricity, increases the available capacity

[1] This positive externality is called "local complements" in Joskow and Tirole (2000).

for the other generator, because only the net transmission flow determines if a line is congested or not.[2] A simple example of this positive externality is a single transmission line with a generator and a price-taking consumer located on each end of the line. Borenstein *et al.* (1998) use a Cournot model with optimal nodal pricing to study this problem.[3] They conclude that limited transmission capacity may reduce the competition among the generators. As this case has been studied in-depth, it will not be discussed in this paper.

Negative externality If we place the generators on the same end of the line they are rivals for the transmission capacity and for the electricity market. If a generator uses the transmission line, he creates a negative externality because he decreases the available capacity for his competitor. This is the setting used in this paper. Our model can easily be extended to any network structure with one consumer and two generators (possibly located on three different nodes).

As long as we assume that only one transmission line is prone to be congested, and that the locations of the generators are such that if they increase production, the flow on this particular line increases.

5.2.4 Market structure

Two market structures are described in the literature: the centralized and the decentralized market.

In the *decentralized market* (Chao and Peck (1996)), the market is responsible for determining electricity prices and transmission prices. Two markets exist which offer complementary products: electricity and physical transmission rights. A generator has to buy physical transmission rights, which give him the right to transport electricity, and to write contracts with consumers for delivery of electricity.

In the *centralized market* (Schweppe *et al.*, 1988 and Hogan, 1992) generators submit bid functions to the network operator. The network operator then sets the production levels and the prices of the players.

In this paper the generators act strategically in one market only. But which of the two competing market structures is more applicable to our model: the decentralized market or the centralized market?

[2]Two electricity flows in opposite directions cancel each other out. Physically only the net flow of electricity is transported. Suppose for example that a generator would like to send 100 MW from A to B, another generator 50 MW from B to A and that the capacity of the line is 70 MW. As the net electricity flow is only 50 MW from A to B, this flow is physically feasible.

[3]Smeers and Wei (1997) assume that each generator decides about sales in each region. Generators can thus discriminate. Implicitly, they assume that reselling of electricity is impossible. In the Borenstein *et al.* (1998) paper, a generator can only decide about his total production. They model a centralized electricity market, where the network operator does not allow for discrimination or a market where the competitive consumers have the time and the possibility to resell their electricity

Given the one-dimensional strategies of the generators, our model is most suited for a *centralized market* where generators submit bids to the network operator. But it can also be applied to *decentralized markets* where the generators are not allowed to withhold electricity, *i.e.* to buy transmission rights without using it. In such a case the generators also have one degree of freedom, and our model can be applied.[4]

The centralized market structure is sometimes extended with a market for financial transmission rights. These financial transmission rights give their owners the congestion rent on a certain transmission line. This can be modelled as a two-stage game: the transmission market operates in the first stage, and the electricity market in the second. Our paper contributes to a better understanding of second stage competition.

Stoft (1999) shows in such a model that the competition for financial rights has a large impact on the distribution of the congestion rent. The generators compete for financial transmission rights, and when there are enough generators with sufficient generation capacity, these rights are traded at their competitive price. As a result, the initial owners of these rights, and not the generators obtain the congestion rent.

Joskow and Tirole (2000) show that this result depends heavily upon the microstructure of the transmission rights market. The distribution of the transmission rights among the initial owners and the amount of free riding among them affects the terms of trade.

5.3 Description of the Game

We model the simplest transmission grid possible: a single transmission line connecting two generators in city North (N) with electricity consumers in city South (S).

The generators $i \in \{1, 2\}$ in North produce a quantity q_i under constant returns to scale. The total production cost of generator i is $c_i \cdot q_i$. The output q_i of each generator is not bounded by technical limitations of their generation plants ($q_i \in^+ \mathrm{R}^+$). With a price of electricity for the end user p, the profit ?i of generator i equals

$$\pi_i = (p - c_i) \cdot q_i \tag{5.1}$$

Consumers consume a quantity q of electricity. They are price takers with a linear inverse demand function $p(q) = a - q$. The two nodes are connected with one transmission line with a limited capacity k. Given the linearity of the model, there is no loss of generality in setting the transmission capacity

[4]An oligopoly model where withholding is allowed has not yet been studied. Joskow and Tirole (2000) study this in a monopoly model. For realistic parameter values, these models have equilibria in mixed strategies. Hence, they are technically difficult to solve.

equal to one.

$$k = 1 \tag{5.2}$$

By assumption, there are no transmission losses, *i.e.* all electricity generated is also consumed.

$$q_1 + q_2 = q \tag{5.3}$$

Also all other transmission costs are assumed to be zero. As transmission capacity is limited it can become scarce, and have an opportunity cost. Thus the unit transmission price τ to transport electricity from North to South is not necessarily equal to zero. With a transmission price τ the generators no longer receive p for their electricity but only $p - \tau$. The profit of generator i is then:

$$\pi_i = (p - \tau - c_i) \cdot q_i \tag{5.4}$$

We define $\theta_i = a - c_i$ as generator i's type. The profit π_i rewrites then as

$$\pi_i = (\theta_i - q - \tau) \cdot q_i \tag{5.5}$$

We assume that the marginal cost of generating electricity is smaller than the consumers' marginal willingness to pay for the first unit of electricity:

$$\theta_i = a - c_i > 0 \tag{5.6}$$

In the rest of this section we look at the benchmark Cournot game without transmission constraint.

Benchmark Cournot Game In a Cournot game, each generator has one decision variable: the quantity q_i to produce. Each player maximizes his profit π_i taking the output q_j of the other player as given:[5]

$$\max_{q_i \geq 0} \pi_i(q_i, q_j) \tag{5.7}$$

The firms have the following Cournot reaction function:

$$q_i^c(q_j) = \max\left\{\frac{\theta_i - q_j}{2}, 0\right\} \tag{5.8}$$

The Nash-equilibrium is the intersection of the two reaction functions. The equilibrium depends thus upon the relative types $(\frac{\theta_i}{\theta_j})$ of the two firms, and falls within three distinct types: (Figure 1.)

$$q_{i,eq}^c = \begin{cases} 0 & \text{if} \quad \frac{\theta_i}{\theta_j} < \frac{1}{2} \\ \frac{2\theta_i - \theta_j}{3} & \text{if} \quad \frac{1}{2} \leq \frac{\theta_i}{\theta_j} \leq 2 \\ \frac{\theta_i}{2} & \text{if} \quad 2 < \frac{\theta_i}{\theta_j} \end{cases} \tag{5.9}$$

[5]The letters $i, j \in \{1, 2\}$ represent arbitrary generators with $j \neq i$.

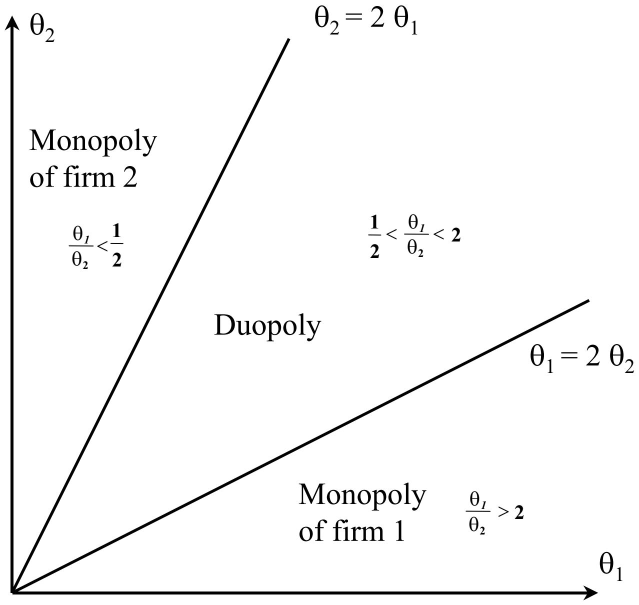

Figure 5.1: Classification of the equilibrium of the standard Cournot game.

- When $\frac{\theta_i}{\theta_j} \leq \frac{1}{2}$,firm i has such a big cost disadvantage that it chooses not to produce. Firm j produces the monopoly quantity.
- When $\frac{1}{2} < \frac{\theta_i}{\theta_j} < 2$,the marginal costs of the firms are comparable, and we get the 'pure' duopoly outcome.
- When $2 \leq \frac{\theta_i}{\theta_j}$,firm i is so competitive that if he produces the monopoly output $\frac{\theta_i}{2}$, the resulting price is lower than the marginal cost of firm j. Firm i is a de-facto monopolist.

In the absence of a transmission constraint, the equilibrium quantity consumed (and transported) is:

$$q^c_{eq} = q^c_{1,eq} + q^c_{2,eq} = \begin{cases} \frac{\theta_2}{2} & \text{if} \quad \frac{\theta_1}{\theta_2} < \frac{1}{2} \\ \frac{\theta_1+\theta_2}{3} & \text{if} \quad \frac{1}{2} \leq \frac{\theta_1}{\theta_2} \leq 2 \\ \frac{\theta_1}{2} & \text{if} \quad 2 < \frac{\theta_1}{\theta_2} \end{cases} \tag{5.10}$$

This quantity is an increasing function of the types ?i of the generators. When the generators have a low cost ci and demand a is high, the demand for transmission is high.

We already made a first classification of the Cournot game: by distinguishing the pure duopoly, and the de facto monopolist (Equation(9)). We can make a second classification: whether the Cournot equilibrium of the game is physically feasible given the transmission capacity k (*i.e.* $q^c_{eq} \leq 1$).

By combining these two classifications we get 6 different outcomes (Figure 2). When the costs of the generators are high, (small θ_i) the total Cournot

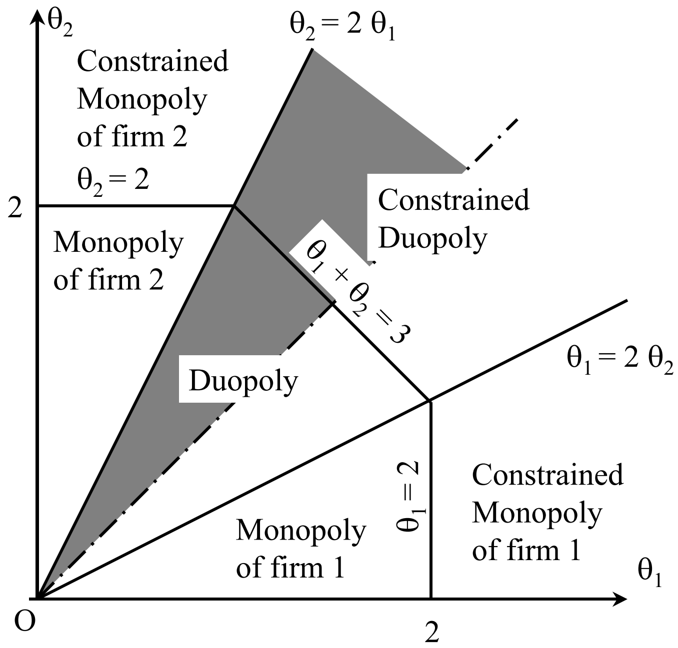

Figure 5.2: Feasibility of the standard Cournot equilibrium.

quantity is small and thus feasible. For small costs, (large θ_i) the Cournot equilibrium is not feasible.

In the rest of the paper we restrict ourselves to the most interesting parameter set of the pure duopoly ($\frac{1}{2} \leq \frac{\theta_1}{\theta_2} \leq 2$) and without loss of generality we assume that generator 1 is the high cost generator and generator 2 the low cost ($c_1 \geq c_2$). The following technical assumption on the relative cost-difference of the generators is thus made: (The region of interest is gray shaded in Figure 2)

$$\frac{1}{2} \leq \frac{\theta_1}{\theta_2} \leq 1 \tag{5.11}$$

We use graphs of the type in Figure 1 and 2 regularly in the rest of the paper. Each point $\vec{\theta} \equiv (\theta_1,\theta_2)$ in this graph represents a different game with different cost parameters. In order to interpret these graphs it is helpful to note that for points close to the 45 degree line generators have similar costs, while for points further away the costs are increasingly asymmetric. For points close to the origin, generators have high costs, and would only like to sell small quantities. For these points the transmission constraint is likely to have little influence. If the costs become smaller, generators would like to produce larger quantities in the Cournot game.

5.4 Generalized Nash Equilibrium

In Oren's (1997) model, each generator maximizes his profit π_i, taking the output of the other player and the transmission constraint as given. The reaction function $q_i^{GNE}(\cdot)$ defines the optimal action of player i for all actions of player j:

$$q_i^{GNE}(q_j;\theta_i) = \arg\max_{q_i} \pi_i^c = [\theta_i - q_1 - q_2] \cdot q_i \tag{5.12}$$

subject to:

$$q_i \leq 1 - q_j \tag{5.13}$$

Equation (13) imposes a common constraint on the strategy spaces of the generators. The equilibria of these kinds of games are called Generalized Nash Equilibria (*GNE*, Harker, 1991).

If constraint (13) is not binding, generator I plays the standard Cournot reaction function $q_i^c(q_j)$ given by equation(8).

On the other hand, if the Cournot quantity is no longer physically feasible $q_i^c(q_j) > 1 - q_j$, the generator adjusts his bid in order not to break the constraint $q_i(q_j) = 1 - q_j$. His reaction function is thus:

$$q_i^{GNE}(q_j) = \begin{cases} q_i^c(q_j) & \text{if} \quad q_j \leq 2 - \theta_i \\ 1 - q_j & \text{if} \quad q_j > 2 - \theta_i \end{cases} \tag{5.14}$$

The intersection of both reaction functions gives the set of *GNE*. This intersection is defined as:

$$\begin{aligned} q_2^{GNE}(q_1) &= q_2 \\ q_1^{GNE}(q_2) &= q_1 \end{aligned} \tag{5.15}$$

Again, the qualitative nature of the equilibrium depends on the players' types.

1. For relatively *high marginal costs* the players play the standard Cournot equilibrium

$$q_{i,eq}^{GNE} = q_{i,eq}^c = \frac{2\theta_i - \theta_j}{3} \tag{5.16}$$

   One such game is presented in Figure 3. This is the second type of graph we use. For a specific pair of cost parameters (θ_1, θ_2) it represents the action space of the players, the reaction functions and the Nash Equilibrium. Given the high marginal costs, the optimal reaction function of the players implies small production levels. The Nash equilibrium is marked with the letter C.

2. For *low marginal costs*, the optimal productions of the players are larger. See for example Figure 4. The intersection of the reaction functions is not unique, but we find *a set* of Nash equilibria:

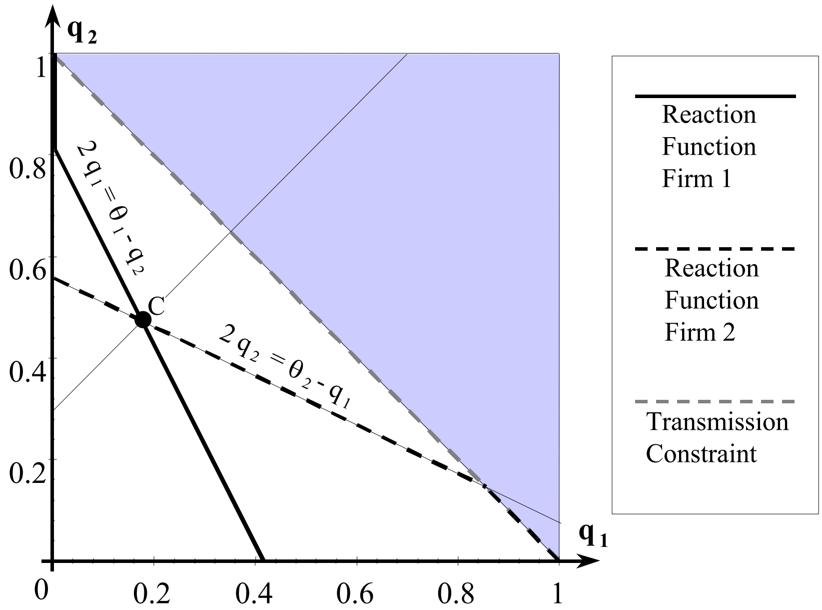

Figure 5.3: *Aon*-rationing and large marginal costs: Nash equilibrium (Shown: θ_1 =0.84; θ_2 =1.12)

$$\left\{ (q_1, q_2) \middle| q_1 + q_2 = 1 \text{and } \forall i : q_i \leq \frac{\theta_i - q_j}{2} \right\} \tag{5.17}$$

The first condition specifies that all transmission capacity is used. The second condition states that each equilibrium must lie below the two standard reaction functions. The set of equilibria is the line A-B in Figure 4. Point C indicates the standard Cournot equilibrium, which would have been played in the absence of a transmission constraint.

Figure 5 represents the parameters associated with each equilibrium. In region A, the equilibrium is the standard Cournot outcome, while in region B there is a line of Nash Equilibria. (The points in the Figure refer to the parameters used in Figures 3 and 4.)

The differences between the *GNE* and the benchmark Cournot game are rather small. The standard Cournot equilibrium is played as long as it is feasible. If it is not feasible, the generators reduce their production until transmission becomes feasible.

Stoft (1999) criticized the *GNE* for not being a Nash equilibrium. Equations (12) and (13) do not define a single-stage game in the classical sense. The profit-function in and is only defined on the triangle Δ, the set of joint physically feasible productions:

$$\Delta = \{(q_1, q_2)\, | q_1 + q_2 \leq 1\} \tag{5.18}$$

In the next section we show that the *GNE* can be implemented as a

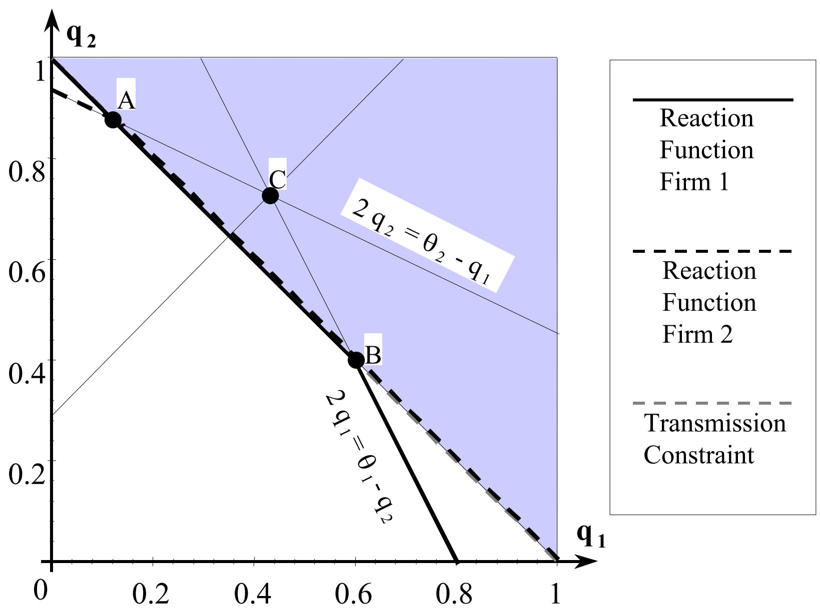

Figure 5.4: *Aon*-rationing and small marginal costs: Nash equilibrium

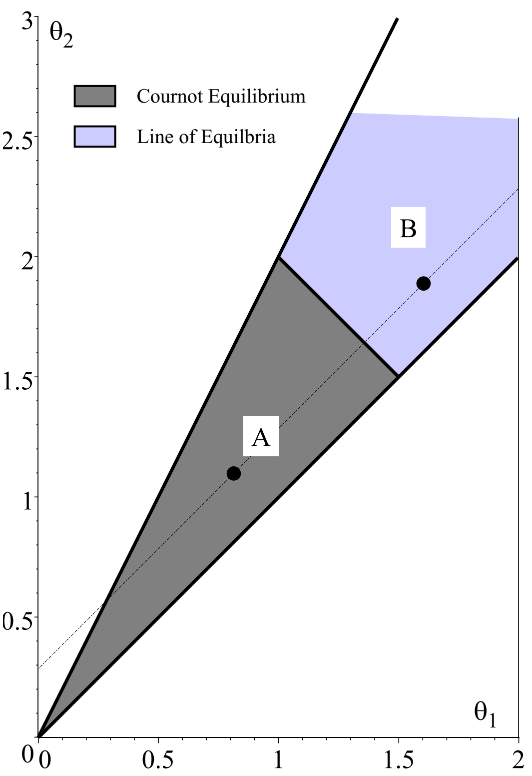

Figure 5.5: Classification of the equilibrium of the game with aon rationing.

standard Nash equilibrium if we make assumptions about the behavior of the network operator.

5.5 Rationing

In the *GNE* model, the variable q_i not only represents the strategy chosen by a generator, but also the actual quantity produced. From now on we will distinguish between them. The actual quantity of electricity that generator i produces is denoted q_i, and the quantity of electricity a generator would like to produce, is his bid Q_i. In order to have a bounded strategy set, we assume that a generator must bid less than the available transmission capacity, *i.e.* he has to choose his bid from the interval $[0, 1]$. The actual production quantities q_i have to be physically feasible ($(q_1, q_2) \in \Delta$). As long as the generators bid less than the available transmission capacity, ($(Q_1, Q_2) \in \Delta$) there is no capacity problem and the network operator allocates the bids to the players.

If the generators bid more than the available capacity $(Q_1, Q_2) \notin \Delta$, the network operator has to assign the generators a lower quantity than they asked for. He rations the capacity of the players using a rationing function f. It is a mapping from the set of strategy profiles upon the set of physically feasible productions:

$$\begin{aligned} f : [0,1] \times [0,1] &\to \Delta \\ (Q_1, Q_2) &\to (q_1, q_2) = (f_1(Q_1, Q_2), f_2(Q_1, Q_2)) \end{aligned} \tag{5.19}$$

which assigns the bids when they are feasible:

$$f(Q_1, Q_2) = (Q_1, Q_2) \ \text{ if } (Q_1, Q_2) \in \Delta \tag{5.20}$$

and rations the bids when they are not

$$f(Q_1, Q_2) \in \Delta \ \text{ if } \ (Q_l, Q_2) \notin \Delta \tag{5.21}$$

We can rewrite the profit of the generators $\pi_i^c(q_i, q_j)$ as a function of the generators' bids:

$$\pi_i^f(Q_i, Q_j) = \begin{cases} \pi_i^c(Q_i, Q_j) & \text{if } \ 0 \le Q_i \le 1 - Q_j \\ \pi_i^c(f_i(Q_i, Q_j), f_j(Q_i, Q_j)) & \text{if } \ 1 - Q_j < Q_i \le 1 \end{cases} \tag{5.22}$$

The profit function of generator i has two different regions. When generator i bids a small quantity Q_i he obtains the standard Cournot profit, but when he bids a large quantity, the generators are rationed.

In the following subsections we calculate the Nash equilibria for three different rationing rules: all-or-nothing, proportional and efficient rationing. The rest of this subsection shows how to calculate reaction functions for a profit function of the type specified by equation(22).

Calculation of reaction functions The reaction function $Q_i^f(Q_j)$ of the game with rationing rule f is the action Q_i that maximizes profit, given the bid Q_j of the other player:

$$Q_i^f(Q_j) = \arg \max_{0 \leq Q_i \leq 1} \pi_i^f(Q_i, Q_j) \tag{5.23}$$

This optimization problem can be solved by splitting up the region $Q_i \in [0,1]$ in two sub-regions $[0, 1-Q_j]$ and $]1-Q_j, 1]$ and calculate the optimal action $Q_i^I(Q_j)$ and $Q_i^{II}(Q_j)$ in both sub-regions.

$$\begin{aligned} Q_i^I(Q_j) &= \arg \max_{0 \leq Q_i \leq 1-Q_j} \pi_i^f(Q_i, Q_j) \\ Q_i^{II}(Q_j) &= \arg \max_{1-Q_j < Q_i \leq 1} \pi_i^f(Q_i, Q_j) \end{aligned} \tag{5.24}$$

Now we compare these two maxima, and choose the action that gives the highest profit.

The optimal reaction for low quantities $Q_i^I(Q_j)$ is precisely the reaction function of the Generalized Nash Equilibrium $Q_i^{GNE}(Q_j)$ as defined in equation14.

Define the function $g^f(Q_j)$ as the difference in profit from bidding the strategy I=GNE (small bid) and bidding strategy II (large bid):

$$\begin{aligned} g_i^f(Q_j) &= \text{profit}(\text{Strategy} = \text{I}) - \text{profit}(\text{Strategy} = \text{II}) \\ &= \pi_i^f(Q_i^{GNE}(Q_j), Q_j) - \pi_i^f(Q_i^{II}(Q_j), Q_j) \end{aligned} \tag{5.25}$$

The value of g is the 'incentive 'of player i to switch from strategy II with a large bid, to strategy I with a small bid. When g is positive it is optimal to restrict the bids and play a small quantity:[6]

$$Q_i^f(Q_j) = \begin{cases} Q_i^{GNE}(Q_j) & \text{if} \quad g_i^f(Q_j) \geq 0 \\ Q_i^{II}(Q_j) & \quad \text{otherwise} \end{cases} \tag{5.26}$$

In the models that we consider $g^f(Q_j)$ has only one root $Q_j^{f,cr}$. The optimal reaction function is thus a cut-off strategy:

$$Q_i^f(Q_j) = \begin{cases} Q_i^{GNE}(Q_j) & \text{if} \quad Q_j \leq Q_j^{f,cr} \\ Q_i^{II}(Q_j) & \text{if} \quad Q_j > Q_j^{f,cr} \end{cases} \tag{5.27}$$

At the critical value the reaction function jumps from $Q_i^{GNE}(Q_j)$ to $Q_i^{II}(Q_j)$.

[6]If g=0, both actions give the same profit, and the player would be indifferent between both actions. We assume that the generator prefers the smallest quantity, to avoid dealing with correspondences.

5.5.1 "all or nothing" rationing

Under the "all or nothing" rationing rule: (index *aon*) the network operator allocates the generators their bids when sufficient capacity is available, but forbids the use of the line when demand exceeds the available capacity.

$$aon_i(Q_i, Q_j) = \begin{cases} Q_i & \text{if} \quad Q_i \leq 1 - Q_j \\ 0 & \quad \text{otherwise} \end{cases} \tag{5.28}$$

Generators make the standard Cournot profit for small Q_i, and obtain zero output for large Q_i.

$$\pi_i^{aon}(Q_i, Q_j) = \begin{cases} \pi_i^c(Q_i, Q_j) & \text{if} \quad Q_i \leq 1 - Q_j \\ 0 & \quad \text{otherwise} \end{cases} \tag{5.29}$$

The reaction function of generator i is defined by:

$$Q_i^{aon}(Q_j) = \arg \max_{0 \leq Q_i \leq 1} \pi_i^{aon}(Q_i, Q_j) \tag{5.30}$$

As bidding more than the available transmission capacity always gives a zero profit, the incentive function $g_i^{aon}(Q_j)$ never becomes negative. The optimal action is thus to play the *GNE* reaction function:

$$Q_i^{aon}(Q_j) = Q_i^{GNE}(Q_j) \tag{5.31}$$

As the reaction functions are identical under *GNE* and under all-or-nothing rationing, so is their intersection, and hence the equilibria. The *GNE* formulation is thus equivalent to the all-or-nothing rationing rule.

Stoft's critique of the *GNE* model is that it is not a standard Nash equilibrium. We showed that by specifying the role of the Network operator it is possible to implement this equilibrium as a Nash equilibrium. By doing so we see that Oren implicitly assumes that the network operator uses "all or nothing" rationing. This "all or nothing" rationing rule is not a very realistic. Forbidding access to the grid is a non-credible threat as it decreases welfare. The problem in Oren's model is thus not the equilibrium concept he uses, but the implicit assumption about the behavior of the network operator. We give a different interpretation of the aon rationing below, which requires a different assumption about the behavior of the network operator.

Stoft's second critique Oren's model is that it is not a good predictor of reality. For low marginal costs, the (*GNE* / *aon*) model predicts that the generators coordinate on one of the infinite number of equilibria. Stoft argues that there is no clear focal point among these equilibria. Therefore there is no reason to believe that the generators play such equilibrium in practice.[7]

[7] Smeers and Wei 1997 use the equilibrium concept of Oren and add the extra specification that the shadow price of constraint (13) must be equal for all players. This extra specification selects a unique equilibrium out of the line of equilibria in Oren's model and can thus be considered as a focal point. The model of Smeers and Wei can also be interpreted as a game were the generators are Rawlsian price takers in the transmission market and compete in quantities in the electricity market. For a further discussion see Willems 2000.

In the literature, we find proportional and efficient rationing instead of "all-or-nothing" rationing. (See for example Tirole (1988)). These rationing rules are discussed in the following two sections.

5.5.2 Proportional rationing.

Under the proportional allocation rule (*prop*) the network operator divides the quantity proportionally to the bids if demand exceeds capacity. [8]

$$prop_i(Q_i, Q_j) = \begin{cases} Q_i & \text{if} \quad Q \leq 1 \\ \frac{Q_i}{Q} & \quad \text{otherwise} \end{cases} \tag{5.32}$$

with $Q = Q_1 + Q_2$. This gives each generator the following profit:

$$\pi_i^{prop}(Q_i, Q_j) = \begin{cases} \pi_i^c(Q_i, Q_j) & \text{if} \quad Q_i \leq 1 - Q_j \\ (\theta_i - 1) \cdot \frac{Q_i}{Q} & \quad \text{otherwise} \end{cases} \tag{5.33}$$

As before, the optimal bid for low Q_i is $Q_i^{GNE}(Q_j)$. For large Q_i, the profit function is an increasing function and the optimal action is to bid 'aggressively' $Q_i^{II}(Q_j) = 1$. The optimal reaction function 'jumps' at the cut off value $Q_j^{prop,cr}$ from the *GNE* bid to the aggressive bid.[9]

$$Q_i^{prop}(Q_j) = \begin{cases} Q_i^{GNE}(Q_j) & \text{if} \quad Q_j \leq Q_j^{prop,cr} \\ 1 & \text{if} \quad Q_j > Q_j^{prop,cr} \end{cases} \tag{5.34}$$

Three games with different parameters are presented in Figures 6, 7 and 8. They show the typical situation with high, intermediate and low marginal costs respectively.

The reaction functions in these figures clearly show jumps.

The Nash equilibrium can be found as the intersection of the two reaction functions. As suggested by observing the Figures 6, 7, and 8, there are three types of equilibria.

- In case A (*high marginal costs*) the standard Cournot equilibrium, with small production quantities is the only equilibrium. (point C in Figure 6.)
- In case B (*intermediate marginal costs*) two equilibria exist in pure strategies: the standard Cournot equilibrium (point C in Figure 7) and the aggressive equilibrium (point D.) In the aggressive equilibrium both players bid $Q_i = 1$ and share the same final production $q_i = \frac{1}{2}$.

[8]The referees judged the proportional rationing to be unrealistic. If a good is sold under it's valuation, players will oversubscribe. Nevertheless, we discuss it here, as in many policy debates proportional rationing is one of the mechanisms that is proposed to deal with congestion. Unlimited over-subscription of transmission capacity can easily be ruled out, if players can only bid for transmission capacity in as far as they have production capacity available. Furthermore, proportional rationing is used in other competitive markets: for example in the initial offerings of stocks.

[9]The derivation can be obtained on the website

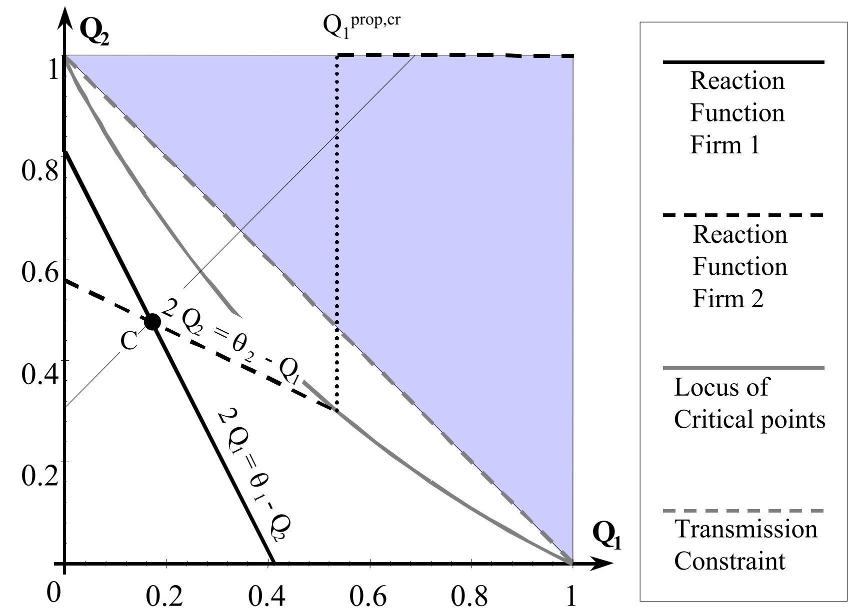

Figure 5.6: *Proportional* rationing and high marginal costs: Nash equilibrium (Shown: θ_1 =0.84; θ_2 =1.12)

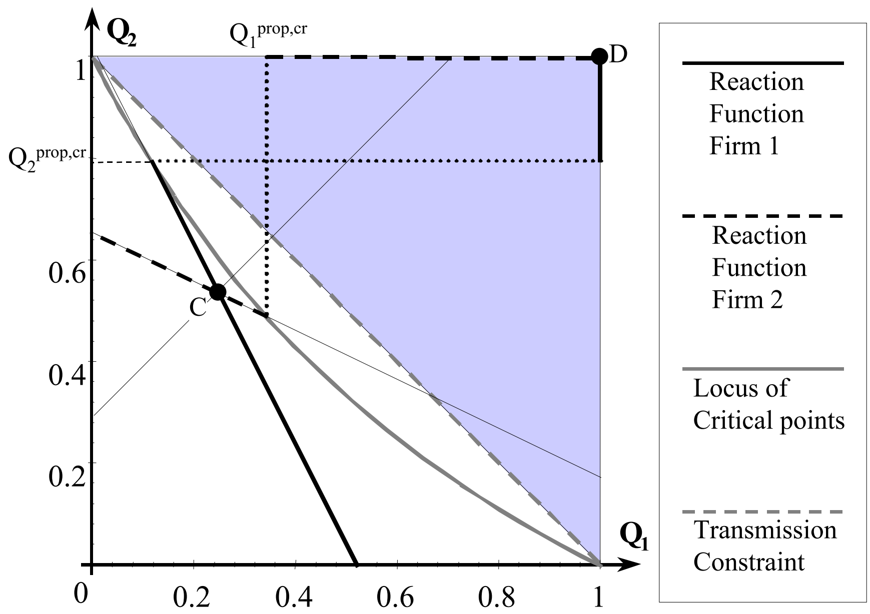

Figure 5.7: *Proportional* rationing and intermediate marginal costs: Nash equilibrium (Shown: θ_1 =1.04; θ_2 =1.32).

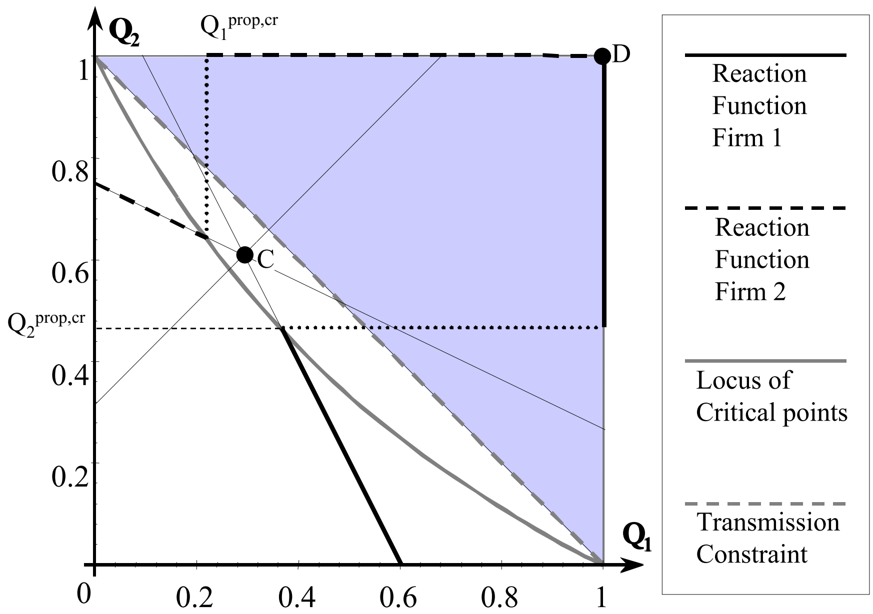

Figure 5.8: *Proportional* rationing and low marginal costs: Nash equilibrium (Shown: θ_1 =1.22; θ_2 =1.50)

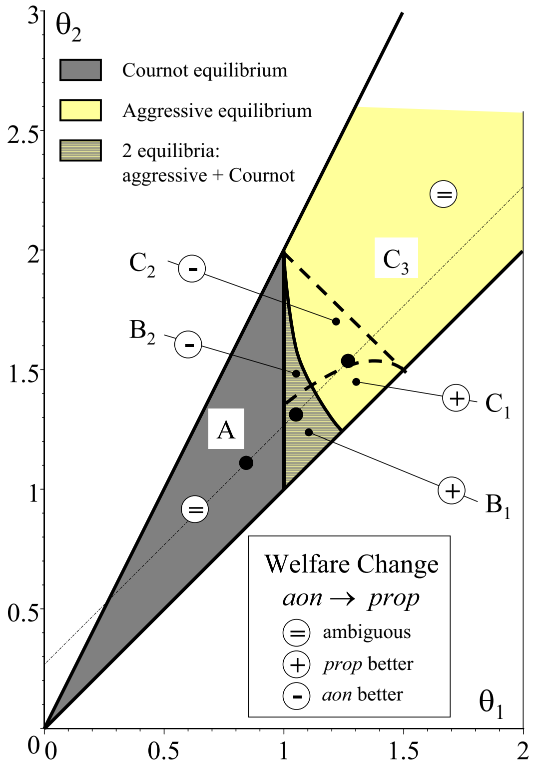

Figure 5.9: Classification of the equilibrium of the game with *proportional* rationing

- In case C (*low marginal costs*) the aggressive equilibrium is the Nash equilibrium. (point D in Figure 8.) Note that the standard Cournot outcome (point C) is technically feasible, but it is *not* an equilibrium.

Figure 9 shows the equilibrium types (A, B or C) as function of the parameter vector $\vec{\theta}$. The points in the figure refer to the examples in figures 6, 7, and 8.

The proportional allocation rule shows one generator buys more of the transmission capacity in order to reduce the output of the other generator. Each generator notes that if he increases his capacity beyond the transmission constraint, the network operator rations both players. The output of his competitor is thus reduced. As both players try to reduce each other's output, both players bid a larger quantity. This occurs when the players coordinate on the aggressive equilibrium (cases B and C).

For *intermediate costs parameters*, the generators even end up producing more than they would produce when there was no transmission constraint. This is the case when total transmission capacity is only slightly above the total Cournot capacity: In the cases B_1, B_2, C_1 and C_2 the standard Cournot equilibrium is played under the "all or nothing" rationing. Under proportional rationing they coordinate on the aggressive equilibrium.[10] Without a transmission constraint, the generators face powerless consumers, while with limited transmission capacity and proportional rationing, the network operator plays off the generators against each other. This higher total production increases consumer surplus. But production efficiency is decreased as both generators produce the same quantity in the aggressive equilibrium where as in the normal Cournot equilibria the low cost generator produces more than the high cost generator. If the cost difference between the generators is small ($\vec{\theta}$ close to the 45° line) the effect on consumers' surplus is larger than the production efficiency loss. This is the case in region B_1 and C_1. In B_2 and C_2, in contrast, welfare declines.

For *low and high cost parameters*, the all-or-nothing and proportional rationing rules do not differ a lot. For high costs (region A) the same equilibrium is played with proportional as with all-or-nothing rationing. For low costs (region C_3) there are an infinite number of Nash equilibria with the all-or-nothing rationing, and welfare can be higher or lower.

The proportional allocation rule shows clearly that the transmission capacity creates a negative externality. In fact, any rationing rule that ensures that a competitor has to decrease production when a generator increases his bid, and that uses the total transmission capacity such that:

$$\frac{\partial f_i(Q_i, Q_j)}{\partial Q_i} = -\frac{\partial f_j(Q_j, Q_i)}{\partial Q_i} > 0 \quad \text{if} \quad Q_i + Q_j = 1 \tag{5.35}$$

[10]Under proportional rationing players can also co-ordinate on the normal Cournot outcome in region B. In that case proportional and all-or-nothing rationing are equal.

induces generators to submit higher bids when the Cournot equilibrium is close to the transmission constraint. Under the all-or-nothing rationing rule, competition for transmission is ruled out by the behavior of the network operator.

Because the network operator has a better bargaining position than the consumers, the generators can be induced to produce more. We do not claim however, that the proportional allocation rule is optimal.

These results are in sharp contrast with models with a positive externality, in which a generator reduces his bid in order to make sure that his competitor reduces production. Positive externalities make the market less competitive.

5.5.3 Efficient rationing

Under efficient rationing a good is allocated to those players who have the highest valuation for it. In our model this implies that the low cost generator (2) always receives his bid, while the high cost generator (1) is rationed when the transmission capacity is insufficient. The efficient rationing rule is the following:

$$eff_2(Q_1, Q_2) = Q_2 \tag{5.36}$$

$$eff_1(Q_1, Q_2) = \begin{cases} Q_1 & \text{if} \quad Q \leq 1 \\ 1 - Q_2 & \text{otherwise} \end{cases} \tag{5.37}$$

The efficient rationing rule requires that the network operator knows the costs of the generators. We assume that this information is used to tax the congestion "rent" $p(1) - c_1$ of the high cost generator if the generators bid more than available capacity. In fact, it is not always a "rent" as it becomes negative when $\theta_1 < 1$. We rule out that the network operator gives a subsidy to the generators. The transmission price is thus[11]

$$\tau(Q_1, Q_2) = \begin{cases} \max\{\theta_1 - 1, 0\} & \text{if} \quad Q > 1 \\ 0 & \text{otherwise} \end{cases} \tag{5.38}$$

This taxation rule is in line with the common opinion that transmission capacity should not be taxed when it is not used at full capacity. It is a naïve implementation of nodal spot pricing, as it does not take into account the behavior of the generators.

Both generators pay this transmission price: the profit of the generators is

$$\pi_i^{eff}(Q_i, Q_j) = \left[\theta_i - eff_i(Q_i, Q_j) - eff_j(Q_j, Q_i) - \tau(Q_j, Q_i)\right] \cdot eff_i(Q_i, Q_j) \tag{5.39}$$

[11] This specification is very similar to the model of Stoft (1999) who uses market clearing. Under efficient rationing the network operator only intervenes when there is congestion. In Stoft's model the network operator also set prices and production levels when there is no congestion.

The *high cost generator* 1 has the same profit function as under the "all or nothing" rationing rule:

$$\pi_1^{eff}(Q_1, Q_2) = \begin{cases} \pi_1^c(Q_1, Q_2) & \text{if} \quad Q_1 \leq 1 - Q_2 \\ 0 & \text{otherwise} \end{cases} \tag{5.40}$$

and his reaction function is thus $Q_1^{GNE}(Q_2)$

$$Q_1^{eff}(Q_2) = Q_1^{GNE}(Q_2) \tag{5.41}$$

The *low cost generator* 2 has a profit function similar to that under proportional rationing. The generator obtains the Cournot profit in a first region, and in the second region his profit is an increasing function of his own bid.

$$\pi_2^{eff}(Q_2, Q_1) = \begin{cases} \pi_1^c(Q_1, Q_2) & \text{if} \quad Q_2 \leq 1 - Q_1 \\ (\theta_2 - \max\{\theta_1, 1\}) \cdot Q_2 & \text{otherwise} \end{cases} \tag{5.42}$$

The optimal action in the first region (small Q_2) is $Q_2^{GNE}(Q_1)$. In the second region ($Q_2 > 1 - Q_1$) the profit function is increasing in Q_2 and the optimal action is the aggressive bidding strategy $Q_2 = 1$. The reaction function of the low cost generator is a cut-off strategy:

$$Q_2^{eff}(Q_1) = \begin{cases} Q_2^{GNE}(Q_1) & \text{if} \quad Q_1 \leq Q_1^{eff,cr} \\ 1 & \text{otherwise} \end{cases} \tag{5.43}$$

The equilibrium is found by intersecting the two reaction functions and is very similar to the all-or-nothing case. In equilibrium the generators never bid more than the available transmission capacity, because the high cost generator finds it always profitable to decrease his bid until the total bid is smaller than the transmission capacity. Only equilibria where the generators bid less than the transmission capacity are possible.

Figure 10 represents the different equilibria of the game with efficient rationing as function of the parameter space $\overrightarrow{\theta}$.

For *high marginal costs* we find the standard Cournot equilibrium. (Region A in the Figure) For some set of parameters an equilibrium in pure strategies does not exist (region B) because the low cost generator prefers to bid aggressively which cannot be an equilibrium.[12]

For *low marginal costs*, we find a line of equilibria as with "all or nothing" rationing. (Region C).[13]

[12] The reaction functions do not cross due to the jump in the reaction function of the low cost generator. Only a mixed strategy equilibrium exists at the jump.

[13] In region C_1 we find exactly the same set of equilibria as with "all or nothing rationing" (Equation 17). In region C_2 we obtain only a subset of these equilibria. Some of the least efficient equilibria, where the low cost firm produces a small quantity, are no longer possible. The low cost generator would have an incentive to play aggressively as he has little to lose.

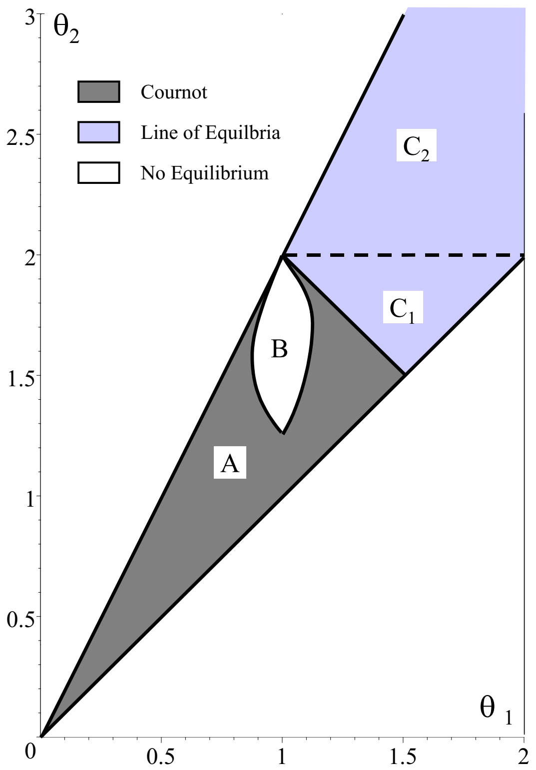

Figure 5.10: Classification of the equilibrium of the game with *efficient* rationing

5.5.4 Who gets the rent?

Above we discussed the effects of the rationing rules on production efficiency and the consumer surplus. This was referred to as short-run efficiency. We did not fully discuss long-run efficiency, which depends upon the distribution of the transmission rent. We use the results of the efficient and all-or-nothing rationing rule to discuss this topic.

Oren reasons that because the generators, in equilibrium, restrict their output to the available transmission capacity, the equilibrium transmission price is equal to zero. [14]

$$\tau = 0 \tag{5.44}$$

With this zero transmission price, the generators receive all congestion rent. Oren states that this conclusion is consistent with the Coase Theorem: "...which supports the argument that in the absence of transaction costs... bargaining will capture all the congestion rents...." This conclusion does not take into account that the network operator is also a player who bargains and can try to obtain some of this rent.

We now look at a different interpretation of the all-or-nothing rationing rule, in which the network operator uses a differentiated transmission tariff:

$$\tau_i(Q_i, Q_j) = \begin{cases} p(1) - c_i = \theta_i - 1 & \text{if} \quad Q > 1 \\ 0 & \text{otherwise} \end{cases} \tag{5.45}$$

When the generators bid a total quantity that is smaller than the available transmission capacity, the network operator does not tax transmission. But when the transmission capacity is not sufficient for the capacity demanded, he taxes each generator separately such that each generator obtains a net price for electricity $p(1) - \tau$ that is equal to his production cost c_i, and obtains a zero profit.[15]

$$\pi_i(Q_i, Q_j) = \begin{cases} \pi_i^c(Q_i, Q_j) & \text{if} \quad Q_i \leq 1 - Q_j \\ 0 & \text{otherwise} \end{cases} \tag{5.46}$$

The network operator can use any rationing rule $f(Q_i, Q_j)$ as this choice does not change the payoff function of the generators. This payoff function is identical to the payoff function under all-or-nothing rationing. We find naturally the same equilibria. We find thus another interpretation of the Generalized Nash equilibrium: the network operator taxes all the rent of the generators when the generators use more than the available capacity. This interpretation is probably more credible than the all or nothing rationing rule. In this new model the generators end up with all the congestion rent.

[14]Oren does not explicitly specify how this transmission price will be set in general. He assumes that there is no reason for a positive transmission price if the generators restrict their bids to the available transmission capacity.

[15]Notice that for $\theta_i < 1$ the transmission tariff becomes negative and is in fact a subsidy.

Because the generators behave strategically, they adapt their behavior and make sure they get a positive profit.

The same conclusion can be drawn under the efficient rationing rule. Here the network operator uses an undifferentiated transmission tariff when there is congestion, and taxes the congestion rent of the high cost firm. This would be optimal in a model with perfect competition. But as one of the generators obtains zero profit when there is congestion, this generator reduces his bid until congestion disappears. So even if the network operator taxes the rent of one generator, he does not obtain any rent.

This is generally true: if the network operator taxes all the rent of one or both of the generators, the generators adapt their behavior and the network operator obtains no rent. A network operator who is interested in obtaining rent, should give the generators an incentive to bid more than the available transmission capacity.[16]

5.6 Optimal Mechanism

In the previous sections we *imposed* some behavioral rules on the network operator. By no means we wanted to suggest that any of these rules is optimal.

In this section we look for such an optimal mechanism. We take the same assumptions as in the previous sections, and add assumptions about the informational structure and the timing of the game.

First, the network operator offers a contract to the generators. Then, the generators accept or refuse this contract, and decide about their production level. Implicitly, this timing gives all bargaining power to the network operator. He can commit not to renegotiate on his offer if it is rejected by a generator.

Each generator knows the production cost of his competitor. It is logical therefore to assume that the network operator has the same information.[17]

In a setting with perfect information the network operator can obtain any allocation that gives a non-negative profit to the generators. He can therefore offer a take-it or leave-it contract (Q_i^{opt}, T_i^{opt}) to the generators. Each generator gets an offer to produce a quantity Q_i^{opt} for which he receives a total transfer T_i^{opt}. If the generators produce a different quantity they receive nothing. These contracts give no decision power to the generators.[18]

[16] Here we assume implicitly that the network operator may only tax the use of the transmission line when there is congestion.

[17] The assumption of perfect information of the network operator has already been made for the efficient rationing rule and in the second interpretation of the all or nothing rationing. If the network operator does not have perfect information, it is still possible to implement the first best outcome, but a large number of other Nash equilibria exist as well.

[18] Of course, they are still free not to produce.

We assume that the network operator optimizes total social surplus, *i.e.* the sum of consumer's surplus, generator's surplus and the surplus of investors in transmission capacity.[19] This social optimum is given by the nodal pricing outcome.[20]

This allocation can be obtained by offering the generators a take-it of leave-it contract: The high cost generator is not allowed to produce, $Q_1^{opt} = 0$ and, the low cost generator is permitted to produce a quantity

$$Q_2^{opt} = \min\{1, \theta_2\} \tag{5.47}$$

in return for a payment

$$T_2^{opt} = c_2 Q_2^{opt} \tag{5.48}$$

In addition to the take-it or leave-it contract, an infinite number of contracts implements the optimal allocation.

However, note that a *fixed* transmission tariff τ, which is independent of the quantity transported, does not implement the optimal allocation.[21]

5.6.1 Discussion

Given perfect information, there is no real difficulty in obtaining the first best outcome. Because the network operator has full information, almost any allocation can be obtained by offering take-it-or-leave it contracts. These optimal contracts give the generators almost no freedom. Optimally only the low cost generator produces, while in the previous rationing rules both generators produce.

In the optimal mechanism the network operator intervenes very heavily in the market, while in the previous models he is only allowed to intervene once transmission is congested.

In practice these extreme contracts are, of course, not observed. Instead, some of the decision power is given to the players. There can be three explanations seem pertinent: A first and obvious reason is that the generators have private information about their costs. Therefore it is optimal to give them some decision power. We can incorporate that in our model by assuming that θ_i is private information, which is unknown to the player j and

[19] If the network operator maximizes his revenue instead, a similar take-it or leave-it contract can be found trivially.

[20] If there are increasing returns to scale in transmission investment, an extension to Ramsey pricing is optimal.

[21] Suppose for instance that $\theta_2 > 1$. The optimal allocation requires a production level $Q_2^{opt} = 1$ and a transmission tariff $\tau = \theta_2 - 1$. But if the generator faces this tariff, he would choose $\frac{1}{2} = \arg\max_{Q_2}(1 - Q_2)Q_2$, which is clearly suboptimal. This result is similar to the classic double marginalization problem (Tirole, 1988)): An upstream player (the network operator) sells an intermediate good (the transmission capacity) to a downstream player (the generator). If he sells the transmission capacity for a linear price (τ), he has only one instrument to obtain two objectives: the optimal production level and the extraction of the rents of the generators.

to the network operator. This would lead to a standard multi-unit auction model.[22]

Second, the network operator does not necessarily pursue general interest. Therefore the regulator imposes some constraints on the contracts that the network operator is allowed to offer. These constraints can reduce the scope for misbehavior or simplify the monitoring of the network operator.

Third, these 'exogenous' constraints on the contracts offered can increase the commitment power of the network operator. Investors of transmission capacity may fear that once their investment in capacity is sunk, the network operator might change his congestion protocol. If these congestion protocols have been set using some general rules, there can be less of a hold-up.

We consider these three topics as important avenues for further research.

5.7 Conclusions

This paper studied the Cournot competition between two generators who use the same transmission line to provide electricity to their consumers.

The central theme of this paper is to show that the role of the network operator is of prime importance for the electricity market, not only for technical reasons but also for economic reasons. In our model with imperfect competition we find two related objectives for the network operator.

If the consumers have no bargaining power, the network operator can organize competition for transmission capacity and use his bargaining power to make the market more competitive.

If the network operator needs revenues to cover his operating costs or to finance new investments, the network operator should not try to tax all the congestion rent of the generators. In this case the generators adapt their behavior and the network operator does not receive any rent.

When the generators can freely set their production level, nodal pricing is not optimal to reach these objectives. It punishes generators for competing with each other, so the generators do not compete.

However, if the network operator has perfect information, the optimal mechanism leaves no margin of decisions to the generators. Thus, nodal pricing becomes optimal.

This mechanism is not likely to be used in practice because there is imperfect information and we may not trust the network operator to maximize social welfare.

The paper makes some strong assumptions. Consumers have a linear demand function, there is only one transmission line, and generators have constant marginal costs, face no production constraints, and set quantities only. Nevertheless the two main results should remain valid under a different set of assumptions. The results can be extended easily in several ways.

[22] In this case some rent has to be given to the efficient generator in order for him to reveal his type.

Replacing the demand function of the consumers and the cost functions of the generators with more general functions would not cause major problems. The transmission network can be generalized to any network where there is one transmission line with congestion, and where a transaction from a generator to the consumers aggravates the congestion on this line. Capacity limits of the plants can be harder to introduce, but the main results would remain.

A justification for the Cournot assumption is that it is widely believed that generators exercise market power by reducing their production quantities, and we wanted to clarify the link with other papers that use the same framework. One of the major criticisms of the model is that there is no price information included. This remains a topic for further research.

This paper is not meant to compare the centralized and decentralized market designs. The model used is far too simple to include the differences between these two designs. This model can be applied to a centralized market as to a decentralized market where withholding of capacity is forbidden.

Appendix 5.A Equilibrium of proportional rationing

The profit a generator obtains by bidding a low quantity $\pi_i^f(Q_i^{GNE}(Q_j), Q_j)$ is a decreasing function of Q_j. See Figure 5.12. This result is intuitive: If Q_j is zero, generator i obtains the monopoly profit, while if Q_j is equal to one, generator i obtains zero profit, as he bids a zero quantity $Q_i^{GNE}(1) = 0$.

5.A.1 Reaction function

We now compare the local optima in the two subregions. If a generator uses strategy I his profit is:

$$\pi_i^{prop}(Q_i^{GNE}(Q_j), Q_j) = (p(Q_i^{GNE}(Q_j) + Q_j) - c_i) \cdot Q_i^{GNE}(Q_j)$$

If he switches to the aggressive strategy, his market size increases from $Q_i^{GNE}(Q_j)$ to $\frac{1}{1+Q_j}$ but the price may drop from $p(Q_i^{GNE}(Q_j) + Q_j)$ to $p(1)$:

$$\pi_i^{prop}(Q_i^{II}(Q_j), Q_j) = (p(1) - c_i) \cdot \frac{1}{1 + Q_j}$$

Generator i switches his strategy when the incentive function changes its sign, which happens at $Q_j^{prop,cr}(\theta_i)$ the solution of $g_i^{prop}(Q; \theta_i) = 0$ (Figure 5.13)

$$Q_j^{prop,cr}(\theta_i) = \begin{cases} \frac{1}{2}\left(\theta_i + 1 - \sqrt{\theta_i^2 + 6\theta_i - 7}\right) & \text{if } \theta_i > 1 \\ 1 & \text{if } \theta_i \leq 1 \end{cases} \tag{5.49}$$

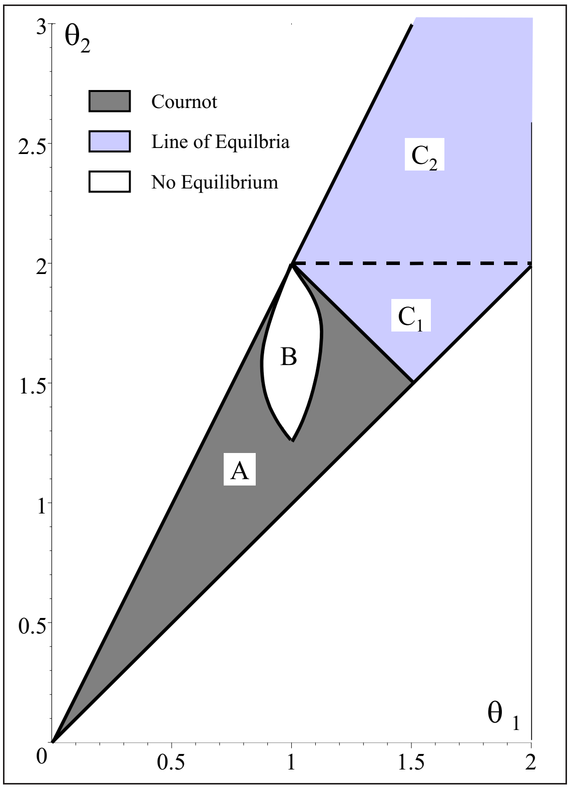

Figure 5.11: The parameter space $\vec{\theta}$ of the game with efficient rationing. The different regions represent the type of reaction function of the low cost firm. In region A the generator plays aggressively, in region B and C he plays aggressively when the bid of the high cost firm Q_1 exceeds a certain critical value Q_1^{cr}. The different colors represent the different equilibrium types. For high costs, the Cournot equilibrium is played, for low costs a line of equilibria exists.

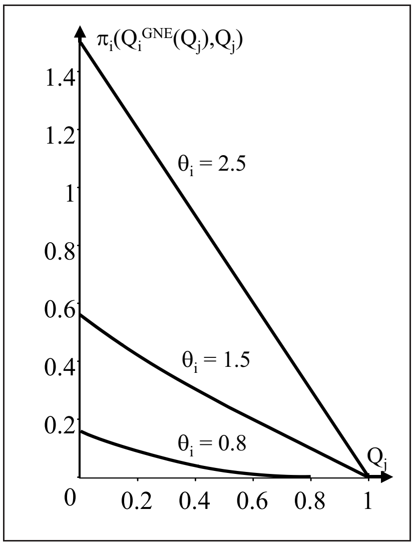

Figure 5.12: Profit of player 1, if player 2 uses $Q_i^{GNE}(\cdot)$

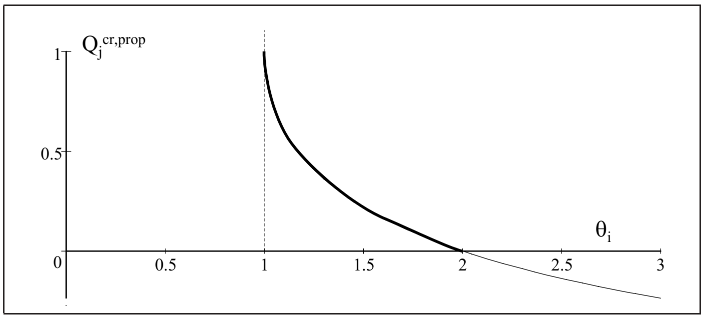

Figure 5.13: Critical values $Q_i^{cr}(\theta_i)$ as function of the parameter θ_i. For $\theta_i > 2$ the generator always plays aggressively. If $\theta_i < 1$ the generator always plays the standard Cournot reaction function.

The optimal reaction function 'jumps' at the cut off value $Q_j^{prop,cr}$ from the GNE bid to the aggressive bid.

$$Q_i^{prop}(Q_j) = \begin{cases} Q_i^{GNE}(Q_j) & \text{if } Q_j \leq Q_j^{prop,cr}(\theta_i) \\ 1 & \text{if } Q_j > Q_j^{prop,cr}(\theta_i) \end{cases} \tag{5.50}$$

5.A.2 Nash Equilibrium

The Nash equilibrium can be found as the intersection of the two reaction functions. The equilibria are found by solving:

$$Q_1^{prop}(Q_2) = Q_1 \tag{5.51}$$
$$Q_2^{prop}(Q_1) = Q_2 \tag{5.52}$$

In equilibrium the total bid can be lower or larger than the available transmission capacity.

When the total bid is smaller than the available transmission capacity, the equilibrium conditions (5.51 and 5.52) can be rewritten as :

$$Q_1^{GNE}(Q_2) = Q_1 \tag{5.53}$$
$$Q_2^{GNE}(Q_1) = Q_2 \tag{5.54}$$
$$Q_2 \leq Q_2^{prop,cr}(\theta_1) \tag{5.55}$$
$$Q_1 \leq Q_1^{prop,cr}(\theta_2) \tag{5.56}$$

The solution of the first two Equations 5.53 and 5.54 are $Q_{1,eq}^{GNE}$ and $Q_{2,eq}^{GNE}$. So we only have to check if these solutions satisfy Equations 5.55 and 5.56. Given the fact that $Q_1^{prop,cr}(\theta_2)+Q_2^{prop,cr}(\theta_2) < 1$, we know that the generators never bid quantities equal to the transmission capacity.

On the other hand when in equilibrium the generators bid more than the available capacity, the following conditions should be satisfied:

$$\begin{aligned} 1 &= Q_1 \\ 1 &= Q_2 \\ Q_1 &> Q_2^{prop,cr}(\theta_1) \\ Q_2 &> Q_1^{prop,cr}(\theta_2) \end{aligned}$$

Also these equilibria can be found simply by checking if $1 > Q_2^{prop,cr}(\theta_1)$ and $1 > Q_2^{prop,cr}(\theta_1)$. We call this the aggressive equilibrium as both generators bid aggressively.

Appendix 5.B Equilibrium of efficient rationing

5.B.1 Reaction function of low cost firm

We now compare the profit of both actions. If the low cost generator uses strategy GNE his profit is:

$$\pi_2^{eff}(Q_2^{GNE}(Q_1), Q_1) = \left[p(Q^{GNE}(Q_1) + Q_1) - c_2\right] \cdot Q^{GNE}(Q_1)$$

By playing aggressively the generator increases his market size from $Q^c(Q_1)$ to 1 but his price drops from $p(Q^c(Q_1)+Q_1)$ to $\min(c_1, p(1))$

$$\pi_2^{eff}(Q_2^{II}(Q_1), Q_1) = (\min(c_1, p(1)) - c_2) \cdot 1$$

The incentive function $g_2^{eff}(Q_1;\theta_1,\theta_2) = \pi_2^{eff}(Q_2^{GNE}(Q_1), Q_1) - \pi_2^{eff}(Q_2^{II}(Q_1), Q_1)$ is a decreasing function in Q_1 and has maximally one root $Q_1^{eff,cr}(\theta_1,\theta_2)$.[23] The reaction function of the low cost generator can be represented as

$$Q_2^{eff}(Q_1) = \begin{cases} Q_2^{GNE}(Q_1) & \text{if } Q_1 \leq Q_1^{eff,cr}(\theta_1,\theta_2) \\ 1 & \text{if } Q_1 > Q_1^{eff,cr}(\theta_1,\theta_2) \end{cases} \tag{5.57}$$

This critical value $Q_1^{eff,cr}(\theta_1,\theta_2)$ depends upon the type $\vec{\theta}$ of both players and has a different definition in three regions A, B, C and D :

$$Q_1^{eff,cr} = \begin{cases} 1 & \text{if } \vec{\theta} \in A \\ \theta_2 - 2\sqrt{\theta_2 - 1} & \text{if } \vec{\theta} \in B \\ \theta_2 - 2\sqrt{\theta_2 - \theta_1} & \text{if } \vec{\theta} \in C \\ \frac{\theta_1 - 1}{\theta_2 - 1} & \text{if } \vec{\theta} \in D \end{cases} \tag{5.58}$$

where $A = \{\theta|\ \theta_1 < 1 \text{ and } \theta_2 < 1\}$, $B = \{\theta|\theta_1 < 1 \text{ and } \theta_2 > 1\}$, $C = \{\theta|\theta_1 > 1 \text{ and } \theta_1 < \theta_2 - (\theta_2 - 1)^2\}$ and $D = \{\theta|\theta_1 > 1 \text{ and } \theta_1 > \theta_2 - (\theta_2 - 1)^2\}$. These regions are represented in Figure 5.11.

5.B.2 Nash Equilibrium

The equilibrium is found by intersecting the two reaction functions. This equilibrium can be calculated quite easily: In equilibrium the generators never bid more than the available transmission capacity, because the high cost generator finds it always profitable to decrease his bid until the total bid is smaller than the transmission capacity. Only equilibria where the generators bid less than the transmission capacity or possible. The equilibrium conditions can thus be written as:

$$Q_2^{GNE}(Q_1) = Q_2 \tag{5.59}$$

$$Q_1^{GNE}(Q_2) = Q_1 \tag{5.60}$$

$$Q_1 \leq Q^{eff,cr} \tag{5.61}$$

The solutions of the first two Equations 5.59 and 5.60, are $Q_{1,eq}^{GNE}$ and $Q_{2,eq}^{GNE}$, so we only have to check wether the third condition is satisfied. For most equilibria this condition is satisfied. The difference of efficient rationing rule and the all-or-nothing allocation rule is the minimal.

[23]As the transmission price τ depends upon the type of player 1, the profit function of the low cost generator depends upon both types and thus also the incentive function g.

Part III

Regulation of the Network Operator

6

Regulating transmission in a spatial oligopoly: a numerical illustration for Belgium

This paper introduces strategic behavior of the electricity network operator in a congested network with imperfect competition for generation. It models a two stage Stackelberg game. First, the network operator sets transmission prices, then generators set output and sales. Several scenarios for the generation market structure and the behavior of the network operator are compared numerically. The calibration of the numerical model is based on data of the Belgian electricity market.

6.1 Introduction

This paper models how a network operator would set transmission tariffs under a number of assumptions. We illustrate, with a numerical model that captures the major technical features of the Belgian electricity system, how transmission prices are a function (1) of the behavior of the network operator, (2) of the level of competition in generation, and (3) of the availability of transmission capacity.

In contrast with most of the literature, the paper explicitly models the strategic behavior of the network operator. For expositional purposes, we present this behavior by considering two stages.

In the first stage, the network operator maximizes his or her objective function by setting transmission tariffs, while taking into account the subsequent actions of generators and consumers. Two alternative objective functions are considered for the network operator: either he maximizes profit, or he maximizes welfare subject to a budget constraint. These objective functions can be seen as two extreme cases, as, in practice, profit will be maximized subject to some form of regulation constraint.

In the second stage, generators take transmission prices as given, while deciding about the level of production in each of their generation plants and about the level of sales to different consumers. The latter are assumed to be price takers. Three alternative scenarios are developed for the generation market. The first scenario is the benchmark and assumes perfect competition in generation. In the second scenario, generation is a monopoly market. As the Belgian electricity market is currently highly concentrated (the largest generator has 83 % of the production capacity), this scenario could be considered as the current situation. The third scenario considers three Cournot players in generation. This can be interpreted as a market where some of the monopolist's production capacity is virtually auctioned, a mechanism that will shortly be implemented in Belgium.

As stated before, the model is illustrated with some numerical simulations. The model that is used for this, is inspired by the Belgian electricity system in terms of the major technical characteristics of both generation and transmission, and in terms of the demand for electricity. The grid and generation characteristics will be described in more detail in section 4.

The structure of the paper is as follows: the next section reviews some relevant and related literature and the sections 3 and 4 describe the structure of the model and the data, respectively. Section 5 discusses simulation results and, finally, section 6 presents conclusions and some extensions for future research.

6.2 Survey of the literature

This section starts with a description of models of imperfect competition in electricity generation without transmission constraints, and continues with a discussion of some Cournot models in which transmission constraints are present. The last part looks at the strategic behavior of the network operator.

6.2.1 Imperfect competition in electricity markets

Due to the non storability of electricity and its highly variable demand, electricity systems tend to feature a mix of base load plants and peak load plants. Peak load plants are typically characterized by high marginal production costs and low investment costs, while base load plants typically have low marginal costs and high investment costs. Peak load plants are only used in periods of high demand, base load plants are used at all times. Peak load power and base load power could therefore be considered as two different goods. To model imperfect competition in such a multi-good market, two types of equilibrium have been developed: the multi unit auction and the supply function equilibrium.

Multi-unit auction In the multi-unit auction, generators bid a price for each plant at which they are willing to supply given capacities[1]. The equilibrium price, determined as the price that clears the market, is applied to all inframarginal units[2]. In this setting, bidders, offering more than one unit of capacity, have an incentive to increase their bids for those plants that are likely to be marginal. Wolfram (1998) finds empirical evidence that, in the England & Wales market, large players effectively try to use their market power in this way.

Multi-unit auctions are particulary hard to model, and do not always have a Nash equilibrium.

Supply Function Equilibrium The supply function equilibrium concept is based on Klemperer and Meyer (1989). Generators choose a continuous and differentiable supply function, which, for each price, specifies the quantity they are willing to generate. Again, the electricity price is established as the market clearing price. Klemperer and Meyer show that an infinite number of Nash equilibria exist when electricity demand is known with certainty. The reason is that only one point on the supply function is required to determine the market clearing price, the remainder of the supply function can be chosen more or less free.

However, if electricity demand is uncertain when generators decide about their supply function, then the latter function has to be appropriate for several situations, and the number of equilibria is reduced[3]. Klemperer and Meyer even show that, under certain conditions, the differentiable supply function equilibrium becomes unique.

Green and Newbery (1992) apply the Klemperer and Meyer model to the two largest generators in the English market[4]. By adding an output constraint for each generator, they can further reduce the set of equilibria. Furthermore, Green and Newbery assume that generators will coordinate on the equilibrium that maximizes total profit. Their model predicts that, in the absence of a threat of entry, the two generators are able to sustain a non-collusive equilibrium in which prices are well above operating costs.

One of the major drawbacks of the two types of models discussed above is that the spatial structure of the electricity market, and therefore the impact of transmission constraints, is omitted. Neither of these two approaches is applicable (yet) in a market with transmission constraints. Most researchers

[1]See for instance the models of Von der Fehr and Harbord (1993).

[2]Other types of auctions can also be considered.

[3]Klemperer and Meyer consider horizontal shifts in demand.

[4]Other studies using this model are Bolle (1992), Newbery (1998), Green (1996) and Rudkevich, Duckworth and Rosen (1998).

therefore opt for some kind of Cournot market, while dropping some of the multi-good aspects of the actual market. In an empirical study, Wolak and Patrick (2001) suggest that Cournot competition is an appropriate representation of the electricity generation market. They argue that the market power of dominant generators is manifested through those generators declaring certain plants unavailable in certain periods[5].

6.2.2 Cournot in generation - Price taking in transmission

Even Cournot models become quite cumbersome when simulations are made for larger networks with transmission constraints. This is the case because generators realize that, with scarce transmission capacity, transmission prices can be influenced, and congestion can be created. Cournot-Nash equilibria are then no longer guaranteed to exist, and rationing rules need to be added to the model. Therefore, this paper assumes that generators behave *à la* Cournot in the energy market (buying and selling of electricity), but are price takers in the transmission market. This approach is inspired by the model of Smeers and Wei (1997, 1999).

Different assumptions can be made with respect to price setting in the transmission market, for example *congestion pricing* (Smeers and Wei, 1997), *regulated pricing* (Smeers and Wei, 1999), and *strategic price setting* (this paper). A short discussion follows.

Congestion pricing Smeers and Wei (1997) assume that the network operator sets prices for using the network on the basis of congestion charges (CC). As long as a line is not used at full capacity, the transmission tariff equals zero. If the line becomes congested, the transmission tariff is increased until demand for transmission equals supply. This can be illustrated for a network with one line of capacity k. With x the demand on the line, and τ the transmission tariff, we have:

$$\tau^{CC}(x) = 0 \text{ IF } |x| < k \tag{6.1a}$$
$$> 0 \text{ IF } x = k \tag{6.1b}$$
$$< 0 \text{ IF } x = -k \tag{6.1c}$$

Congestion pricing can be interpreted as the result of assuming that the network operator behaves perfectly competitive. Thus, the network operator acts as a price taker in the transmission market and appears to be unaware of his market power in that market. Congestion charges can be implemented when the network operator is forced to sell *all* transmission capacity in an

[5]Other studies using Cournot competition are Oren (1997) Stoft (1997), Borenstein, Bushnell and Stoft (1998), Borenstein, Bushnell and Knittel (1999), Borenstein and Bushnell (1999), Hogan (1997), Cardell, Hitt and Hogan (1997).

auction, is not allowed to withhold capacity from the market, and is not allowed to set a minimal reservation price for the transmission rights.

Regulated prices Wei and Smeers (1999) study *regulated transmission prices*. Here, the transmission charge is the sum of two parts: a congestion charge τ^{CC}, and a regulated charge τ^{R} [6]:

$$\tau(x) = \tau^{CC}(x) + \tau^{R}(x) \tag{6.2}$$

The term $\tau^{R}(x)$ is set according to a regulatory rule which depends on the use of the line. They study two types of regulatory rules: *marginal cost pricing* and *average cost pricing*. The average cost rule sets the regulated charge for a transmission line equal to the average cost of building a new transmission line. With the marginal cost rule, the regulated charges are set according to the marginal cost of building transmission lines.

The congestion charge $\tau^{CC}(x)$ is required to clear the market when the demand for transmission is in excess of available capacity at a transmission price equal to the regulated charge $\tau^{R}(x)$. Wei and Smeers assume that congestion charges are *not* used to refund the network operator for building new transmission capacity[7].

The Smeers and Wei model and the model in this paper are different because the first model does not include Kirchhoff's laws. On the other hand, Smeers and Wei also model investment in new transmission capacity, something which is not included in this paper's model.

Prices chosen by the network operator In this paper, the network operator is no longer assumed to behave as a passive player, but rather as a Stackelberg leader in a two-stage game. In stage one, he maximizes his objective function by setting transmission prices, while taking into account the effect of its pricing decision on the strategic behavior of the players in the generation market. Transmission demand is thus assumed to be price responsive. In the second stage, generators behave *à la* Cournot.

Two alternative and extreme assumptions with respect to the network operator's objective function are discussed in the paper: *profit maximization* and *welfare maximization subject to a budget constraint*. Network operation is commonly accepted to be a natural monopoly, and, therefore, without regulation the network operator would simply maximize profit (Case 1). The second alternative assumption is that regulation is perfect, and that the network operator maximizes welfare subject to a budget constraint (nonnegative profit).

[6] Wei and Smeers (1999) give a different interpretation to the congestion charges than we do here. They look for a Generalized Nash Equilibrium where transmission constraints are internalized. In that case, congestion charges are internal multipliers. See also the previous chapter, and the introduction.

[7] It has often been argued that congestion payments should not go to the network operator as this could give the wrong incentives.

6.3 The model

Define the sets F and G as the sets of generation firms and generation plants. Let G_f be the set of generation units owned by generation firm $f \in F$.With I being the set of network nodes, G_i denotes the generation plants at node $i \in I$, and G_{fi} the generation plants at node i owned by firm f. The *network* contains a number of nodes $i \in I$. Furthermore, let A be the set of transmission lines in the network, with $a(i, j) \in A$ the line connecting the nodes i and j.

For notational simplicity, the model will be further described as if it concerned a one period model, *i.e.* a model that does not distinguish between peak and off-peak periods. However, the numerical simulations discussed in section 5 also cover a case that differentiates between peak and off-peak demand in a 4-period model.

The model distinguishes three types of players: consumers, generation firms and the network operator.

Consumers are price takers. At node i, they consume s_i units of electricity. Their inverse demand for electricity, denoted as $p_i(s_i)$, is downward sloping and concave. Consumer prices include compensation for both the generation and the transmission of electricity.

Generation firm $f \in F$ maximizes profits, while acting as a price taker in transmission. At node i, it owns the generation plants $g \in G_{fi}$.

Electricity generation in *plant* g is q_g and the generation cost is $C_g(q_g)$. Total generation costs are convex, with fixed generation costs normalized to zero. The generation capacity of plant g is labelled $\bar{q}_g$. Output should be nonnegative, and cannot exceed available generation capacity. Therefore, we have

$$0 \leq q_g \leq \bar{q}_g$$

The *network operator* or *transmission company* either maximizes profit or social welfare, depending on the assumptions taken later on. The transmission company sets a nodal transmission charge τ_i^c for consumers and τ_i^g for generators. This is the per unit payment generators have to make for injecting power, and that consumers have to pay to take power from the grid. These charges can be different. For instance, a generator who generates electricity in node i and sell electricity in node j will pay $\tau_i^g + \tau_j^c$. Only the sum of the consumer and generation transmission charge is important, and therefore one of the charges can be set equal to zero without loss of generality.

As explained before, the model has two stages. In the first stage, the transmission operator sets transmission prices. In the second stage, generation firms play a Cournot game in which transmission prices and their competitor's quantities are assumed as given. The next subsection describes the second stage of the game.

6.3.1 The second stage

Each firm f observes the transmission charges τ_i^p and τ_i^c as set by the network operator and plays a Cournot game. A firm f collects revenue by selling s_{fi} units of electricity at node i at the per unit price p_i. Firms also set the production level q_g ($g \in G_f$) at each of their plants Their competitor's sales in node i, denoted by $\tilde{s}_{-fi}$, are taken as given. Apart from generation costs, firms also pay a transmission cost τ_i^p for injecting electricity to the network at node i, and τ_i^c for the delivery of electricity to node i. This results in the following profit function for generation firm f,

$$\Pi_f^{Gen} = \sum_{i \in I} (p_i - \tau_i^c) \cdot s_{fi} - \sum_{i \in I} \sum_{g \in G_{f_i}} \left[C_g(q_g) + \tau_i^p q_g\right] \tag{6.3}$$

The nodal price p_i that is received by generator f depends on the total sales in that node, *i.e.*

$$\begin{aligned} p_i &= p_i(s_i) \\ s_i &= s_{fi} + \tilde{s}_{-fi} \end{aligned}$$

where a tilde indicates that the variable is considered as given. In equation 6.3, the first term reflects revenues from electricity sales net of transmission charges paid at the consumption nodes. The second term reflects generation costs and transmission charges to put the electricity on the network. Summarizing, we have the following maximization problem for a generator:

$$\max_{s_{fi}, q_g (g \in G_f)} \Pi_f^{Gen} = \sum_{i \in I} (p_i(s_i) - \tau_i^c) \cdot s_{fi} - \sum_{i \in I} \sum_{g \in G_{f_i}} \left[C_g(q_g) + \tau_i^p q_g\right]$$

Subject to:

$$\begin{aligned} 0 \leq \ q_g \leq \ \bar{q}_g \quad & \left(\underline{\mu}_g, \overline{\mu}_g\right) \quad \forall g \in G_f \\ \sum_{i \in I} s_{fi} = \sum_{g \in G_f} q_g \quad & \left(\lambda_f^p\right) \\ s_i = s_{fi} + \tilde{s}_{-fi} \quad & \forall i \in I \end{aligned} \tag{6.4}$$

As noted before, the first constraint reflects generation capacity constraints. The second constraint represents the energy balance at the firm level, *i.e.* total output should equal total sales. The last constraint represents demand. This constraint has no multiplier as it is substituted into the objective function and the other constraints before derivatives are taken.

The following first order conditions are then derived:

$$\frac{\partial C_g(q_g)}{\partial q_g} + \tau_i^p + \underline{\mu}_g - \overline{\mu}_g = \lambda_f^p \quad \forall g \in G_{fi}, \forall i \in I \tag{6.5}$$

$$p_i + \frac{\partial p_i(s_i)}{\partial s_i} s_{fi} - \tau_i^c = \lambda_f^p \quad \forall i \in I \tag{6.6}$$

These are the standard first-order conditions for profit maximization, *i.e.* as long as generation constraints are not binding, marginal revenue equals marginal cost in all market segments. The Lagrange multiplier of the energy balance constraint λ_f^p, is the value of energy *in the network* for generation firm f. This value is different for every firm.

Cost minimization requires that each firm equalizes the sum of the marginal cost and the generation charge at all generation plants. Profit maximization requires that marginal revenues net of consumption charges are equalized.

Each firm‘s reaction function with respect to the sales s_{-fi} and the transmission charges, τ_i^c and τ_i^g can be derived from the equations 6.4, 6.5 and 6.6.

In the remainder of this paper, we assume that the generation constraints are not binding ($\underline{\mu}_g = \overline{\mu}_g = 0$). Without this assumption, the network operator's problem becomes intractable. The firms will thus not choose corner solutions. This is the case when (1) the marginal costs are zero for zero output

$$\lim_{q_g \to 0} \frac{\partial C_g(q_g = 0)}{\partial q_g} = 0$$

and (2) sufficiently large at full output

$$\lim_{q_g \to \bar{q}_g} \frac{\partial C_g(q_g)}{\partial q_g} = \infty$$

Electricity transmission The model should allow simulating of the effects of structural and regulatory changes in the electricity sector. Therefore, the technical features of the electricity system, especially at the level of electricity transport, should also be captured by the model. Electricity transport is subject to physical constraints. These constraints have an impact on the power flow through the network and therefore potentially also on the pricing of transmission services. In this paper we concentrate on active power and we adopt a simplified DC flow model without losses.[8]

Each line in the network is characterized by a transmission capacity and its admittance. For example, the line a (i,j) connecting the nodes i and j has a capacity $\bar{Q}_{a(i,j)}$ and an inductance $Y_{a(i,j)}$[9]. Denoting the flow over the line a as Q_a, we must have

$$Q_a \leq \bar{Q}_a \quad \forall a \in A \tag{6.7}$$

[8]Such a model assumes that line resistance is small relative to reactance, that voltage magnitudes are the same at all nodes, and that voltage angles between nodes at opposite ends of a transmission line are small. Engineers often use the linearized model of the network for long term planning.

The alternative, AC-power flow, was used in a previous version of the program, but did not give fundamentally different results.

[9]The shorthand a will be used to indicate a line $a\,(i,j)$ if this can be done without creating confusion.

Transmission must be smaller than the available transmission capacity. This is also called the thermal constraint of line a, because the line's temperature increases too much if the line carries larger flows.

The flow over a line $a\,(i,j)$ is proportional to the difference of the phase angles in the begin and end point, *i.e.*

$$Q_{a(i,j)} = Y_{a(i,j)}\,(\delta_i - \delta_j) \qquad \forall a\,(i,j) \in A \tag{6.8}$$

As there is one degree of freedom in choosing phase angles, one phase angle, located at the so-called swing node, is set equal to zero.

$$\delta_i = 0, i = \text{swing node} \tag{6.9}$$

The physical properties of the network can be summarized by a set of nodal equations, and a set of line equations. In each node, the flows entering and leaving the node should balance, *i.e.*

$$q_i - s_i = \sum_{j \in I} Q_{a(i,j)} \quad \forall i \in I \tag{6.10}$$

with s_i, q_i the total consumption and generation in node i:

$$s_i = \sum_{f \in F} s_{fi} \quad \forall i \in I \tag{6.11}$$

$$q_i = \sum_{g \in G_i} q_g \quad \forall i \in I \tag{6.12}$$

The left hand side of 6.10 is the surplus of local production in node i (=production − consumption in node i). The right hand side is the sum of the flows leaving node i.

Equations 6.7 - 6.9 describe the transmission possibilities of the network, *i.e.* they define the production feasibility set of the network operator.

Security of supply The network operator also needs to secure the supply of electricity. A minimal requirement for this is that, if unexpectedly a line goes out of service the remaining lines should still be able to transport all supplied electricity. This is the so-called $n-1$ rule, *i.e.* if a line $\alpha \in A$ breaks down, the set of the remaining lines $A/\{\alpha\}$ should be able to transport the power over the network. After a contingency, the flows redistribute themselves over the network, and these new flows should still be feasible given the thermal constrains of the networks. Clearly, taking into account the $n-1$ rule has an impact on the constraints 7, 8, 11 and 12. These equations become

$$q_i - s_i = \sum_{a(i,j) \in A \setminus \{\alpha\}} Q^{\alpha}_{a(i,j)} \quad \forall i \in I \tag{6.13}$$

$$Q^{\alpha}_{a(i,j)} = Y_{a(i,j)}\left(\delta^{\alpha}_i - \delta^{\alpha}_j\right) \qquad \forall \alpha \in A, \forall a \in A \setminus \{\alpha\} \tag{6.14}$$

$$\delta_i^\alpha = 0, \qquad i = \text{swing node}, \forall \alpha \in A \tag{6.15}$$

$$Q_a^\alpha \leq \bar{Q}_a \quad \forall a \in A \backslash \{\alpha\} \tag{6.16}$$

The variable Q_a^α denotes the flow on line a when line α fails. Each of these constraints must be satisfied for each potential line breakdown. The equations 6.7 to 6.16 form the network equations of the model.

6.3.2 The first stage

The network operator is either a profit-maximizing firm or a welfare maximizing firm, subject to a budget constraint. The objective is maximized by setting consumption and generation transmission charges (τ_i^c and τ_i^p), which can be differentiated over the nodes. It is assumed that the cost of providing transmission services is separable into operating costs and capacity costs. In the present model, operating costs and network losses are neglected. Therefore, only the capacity costs B remain.

The profit of the network operator is then equal to:

$$\Pi^{tr} = \sum_{i \in I} (\tau_i^c s_i + \tau_i^p q_i) - B \tag{6.17}$$

The first term between brackets is the revenue of selling transmission services to consumers at node i. The second term is the revenue of selling transmission to the generators. The last term represents capacity costs. By assumption, capacity costs are fixed.

Profit maximization With profit maximization, the network operator maximizes profits Π^{tr} subject to

the *energy balance* at the firm level,

$$\sum_{i \in I} s_{fi} = \sum_{g \in G_f} q_g \quad \forall f \in F \backslash \{f_1\} \tag{6.18}$$

the *Cournot behavior (Sales - Production)*

$$p_i(s_i) + \frac{\partial p_i(s_i)}{\partial s_i} s_{fi} - \tau_i^c = \lambda_f^p \quad \forall i \in I, \forall f \in F \tag{6.19}$$

$$\frac{\partial C_g(q_g)}{\partial q_g} + \tau_i^p = \lambda_f^p \quad \forall i \in I, \forall f \in F, \forall g \in G_{fi} \tag{6.20}$$

and the ten *network equations* 6.7 - 6.16:

$$q_i - s_i = \sum_{j \in I} Q_{a(i,j)} \quad \forall i \in I \tag{6.21}$$

$$Q_a \leq \bar{Q}_a \quad \left(\gamma_t^{tr}\right) \quad \forall a \in A \tag{6.22}$$

$$Q_{a(i,j)} = Y_{a(i,j)} \left(\delta_i - \delta_j\right) \quad \forall a \in A \tag{6.23}$$

$$\delta_i = 0, \quad i = \text{swing node} \tag{6.24}$$

$$s_i = \sum_{f \in F} s_{fi} \quad \forall i \in I \tag{6.25}$$

$$q_i = \sum_{g \in G_i} q_g \quad \forall i \in I \tag{6.26}$$

$$\tau_i^c = 0 \quad i = \text{swing node} \tag{6.27}$$

$$q_i - s_i = \sum_{a(i,j) \in A \backslash \{\alpha\}} Q_a^\alpha \quad \forall \alpha \in A, \forall i \in I \tag{6.28}$$

$$Q_{a(i,j)}^\alpha = Y_{a(i,j)} \left(\delta_i^\alpha - \delta_j^\alpha\right) \quad \forall \alpha \in A, \forall a \in A \backslash \{\alpha\} \tag{6.29}$$

$$\delta_i^\alpha = 0, \quad i = \text{swing node}, \forall \alpha \in A \tag{6.30}$$

$$Q_a^\alpha \leq \bar{Q}_a \quad \forall \alpha \in A, \forall a \in A \backslash \{\alpha\} \tag{6.31}$$

Note that the set of network equations implies global energy balance, *i.e.* total production is equal to total consumption. Therefore one of the energy balances of the generators can be dropped from the optimization problem.

The two constraints that describe the Cournot behavior of the generator define a non-convex constraint. Therefore the problem does not need to have a unique local optimum.

Welfare maximization Under welfare maximization the network operator maximizes

$$W = \sum_{i \in I} \int_0^{s_i} p_i\left(t\right) dt - \sum_{g \in G} C_g\left(q_g\right) \tag{6.32}$$

subject to the network constraints 6.7 - 6.16, the Cournot behavior of the generators (6.18 - 6.20) and the budget constraint:

$$\sum_{i \in I} \left(\tau_i^c s_i + \tau_i^p q_i\right) - B = \Pi^{tr} \geq 0 \tag{6.33}$$

This latter constraint is added in order to avoid that the network operator goes bankrupt.

6.4 Data and calibration

Before continuing with the simulations, we discuss the data that have been used as an input for the model. Also, the calibration procedure will be described. The choice of the technical features of the transmission grid and of the available generation plants is inspired by the Belgian electricity system. This is, however, not the case for the regulatory framework. Here, we make two extreme assumptions, *i.e.* perfect regulation versus no regulation.

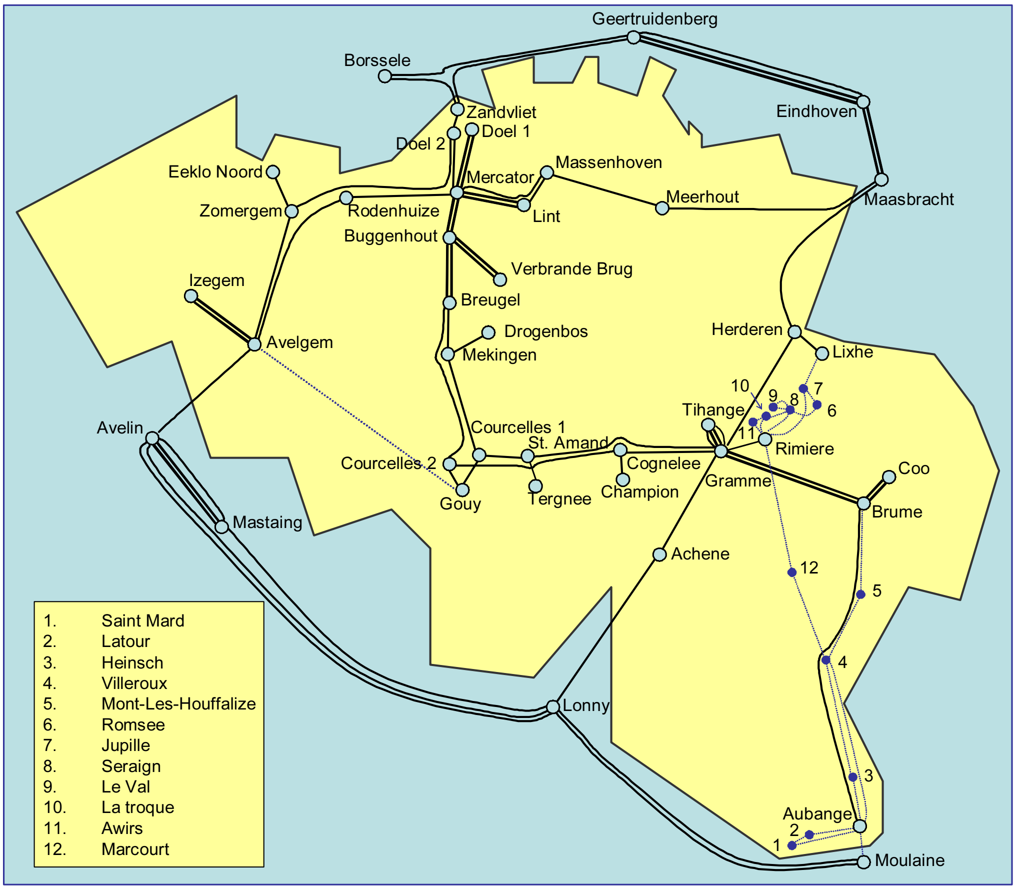

Figure 6.1: The Belgian high voltage network, situation in 2002.

6.4.1 The Network

Figure 6.1 shows the network that has been used. It consists of 55 nodes and 92 lines and includes all the Belgian 380 kV and 220 kV transmission lines, but also some 380 kV lines in The Netherlands and France because they are important for the flows inside the Belgian network. The full lines on the graph are 380 kV lines, the dotted lines are 220 kV lines. The line between Gouy and Avelgem represents several lines of the 110 kV network that connect both nodes.[10]

The data of the lines are given in the Table 6.1. It gives, for each line, information on origin and destination, voltage level, admittance, thermal capacity, and whether the line is used in the contingency analysis.

Some of the columns require more explanation. The admittance of each line is normalized on the basis of the reference voltage level of the lines ($V^{ref} = 380,\ 220$ or $110\ kV$) and the reference power level ($S^{ref} = 1MW$).

[10]Network data was kindly provided by Peter Van Roy and Konrad Purchala of the Department of Electrical Engineering.

The normalized admittance is equal to

$$Y_a = \frac{(V_a^{ref})^2}{S^{ref}\sqrt{X_a^2 + R_a^2}} \tag{6.34}$$

with X_a $[Ohm]$ and $R_a[Ohm]$ the resistance and the reactance of the lines.

The last column of Table 6.1 indicates whether the line is checked for the $n-1$ security constraint. For a line indicated with Y (=Yes) we make sure that when it breaks down that the remaining (92-1) lines can transport the electricity. The $n-1$ rule is checked for all Belgian 380 kV lines, except for some loose ends. Line 34 (Drogenbos - Mekingen) is such a loose end, *i.e.* Drogenbos can only be supplied via the line from Mekingen. Using the $n-1$ rule for this line makes no sense when we do not include lower voltage levels.

The $n-1$ rule is not imposed for the interconnections with France and The Netherlands and for the lines within these countries, because sufficient or adequate information is lacking.

6.4.2 Electricity generation

Table 6.2 summarizes relevant data on the 51 generation units located in the grid. Total available generation capacity equals 13 405 MW. The data are based upon the year 2002.[11]

The first column gives the node at which the generation unit is attached, the second the name of the plant, and the third the fuel type of the plant. The columns four and five give the marginal cost parameter C_g (defined below) and the maximal capacity of the plants $\bar{q}_g$.

In the simulations, three alternative scenarios are considered w.r.t. the functioning of the generation market. First, we assume a generation monopoly, *i.e.* all generation units are owned by one profit maximizing generator. The second scenario considers three profit maximizing generators, having an approximate market share in generation capacity of 43%, 34% and 23%, respectively. The last column in Table 3 provides information on the assumed generation ownership structure in this case. Finally, the third scenario assumes perfect competition in generation.

Approximately 1070 MW of smaller generation plants are not included in the model. These are mainly combined heat and power generation units (970 MW), and some small hydro units (90 MW). We assume that in any time period, 50 % of these plants produce electricity.

Each player maximizes profit, taking into account plant characteristics. Generation decisions are described by the first order conditions 6.5. The player's generation decisions are highly non-linear at the zero production level and at the maximal capacity of each plant. Therefore, the model in this

[11]Some of the data was kindly provided by Leonardo Meeus and Kris Voorspools of the Departments of Electrical and Mechanical Engineering, respectively. Data was also taken from several editions of the BFE statistical yearbook, the annual report of Electabel.

# line	FROM	TO	V (kV)	Y (p.u.)	$\bar{Q}_{(i,j)}$ (MW)	N-1 (Yes)
1	Achene	Gramme	380	13165	1316	Y
2	Achene	Lonny	380	8071	1179	
3	Aubange	Brume	380	5094	790	Y
4	Avelgem	Avelin (FR)	380	11321	1179	Y
5	Avelgem	Izegem	380	21310	1420	Y
6	Avelgem	Izegem	380	21310	1420	
7	Avelgem	Rodenhuize	380	9026	1420	Y
8	Avelgem	Zomergem	380	12234	1350	Y
9	Borssele (NL)	Zandvliet	380	10931	1650	
10	Bruegel	Buggenhout	380	30545	1420	Y
11	Bruegel	Buggenhout	380	31090	1350	Y
12	Bruegel	Courcelles 2	380	10268	1420	Y
13	Bruegel	Mekingen	380	34468	1350	Y
14	Brume	Coo	380	242820	1350	Y
15	Brume	Coo	380	242820	1350	Y
16	Brume	Gramme	380	10963	1420	Y
17	Brume	Gramme	380	10963	1350	Y
18	Buggenhout	Mercator	380	31332	1420	Y
19	Buggenhout	Mercator	380	31780	1350	Y
20	Buggenhout	Verbrande Brug	380	22372	1420	Y
21	Buggenhout	Verbrande Brug	380	22372	1420	Y
22	Champion	Cognelee	380	134987	1420	
23	Cognelee	Courcelles 2	380	11991	1420	Y
24	Cognelee	Gramme	380	16982	1420	Y
25	Courcelles 1	Gouy	380	284443	1350	Y
26	Courcelles 1	Mekingen	380	14534	1350	Y
27	Courcelles 1	StAmand	380	38569	1350	Y
28	Courcelles 2	Gouy	380	269973	1420	Y
29	Doel 1	Mercator	380	23241	1420	Y
30	Doel 1	Mercator	380	21295	1350	Y
31	Doel 2	Mercator	380	21295	1350	Y
32	Doel 2	Zandvliet	380	66471	1420	Y
33	Doel 2	Zomergem	380	7048	1350	Y
34	Drogenbos	Mekingen	380	47128	1420	
35	Eeklo Noord	Zomergem	380	40429	1420	
36	Geert	Zandvliet	380	8596	1650	
37	Gramme	Herderen	380	11391	1350	Y
38	Gramme	Rimiere	380	33255	1350	Y
39	Gramme	Saint Amand	380	8610	1350	Y
40	Gramme	Tihange	380	147492	1420	Y
41	Gramme	Tihange	380	186733	1420	Y
42	Gramme	Tihange	380	167687	1350	Y
43	Gramme	Tihange	380	167687	1350	Y
44	Herderen	Lixhe	380	47621	1420	Y
45	Herderen	Maasbracht (NL)	380	9138	1350	
46	Lint	Massenhoven	380	34441	1420	Y
47	Lint	Mercator	380	23019	1420	Y
48	Lint	Mercator	380	23019	1420	Y
49	Maasbracht (NL)	Meerhout	380	6998	1420	
50	Massenhoven	Meerhout	380	14942	1420	Y
51	Massenhoven	Mercator	380	13797	1420	Y
52	Mercator	Rodenhuize	380	14204	1350	Y
53	Saint Amand	Tergnee	380	64753	1420	

Table 6.1: Lines used in the numerical model.

# line	FROM	TO	V (kV)	Y (p.u.)	$\overline{Q}_{(i,j)}$ (MW)	N-1 (Yes)
54	Aubange	Belval	220	8601	400	
55	Aubange	Heinsch	220	11686	240	
56	Aubange	Latour	220	8534	345	
57	Aubange	Moula	220	8839	400	
58	Aubange	StMard	220	6269	345	
59	Aubange	Villeroux	220	3644	240	
60	Awirs	Le Val	220	20157	410	
61	Awirs	Rimiere	220	18398	375	
62	Brume	Montlez Houffalize	220	6462	510	
63	Harnoncourt	Saint Mard	220	188066	345	
64	Heinsch	Villeroux	220	5339	240	
65	Jupille	Lixhe	220	14885	541	
66	Jupille	Rimiere	220	5963	410	
67	Jupille	Romsee	220	23987	300	
68	Latour	Sint Mard	220	23716	345	
69	La Troque	Seraing	220	53081	400	
70	La Troque	Seraing	220	53081	400	
71	Le Val	Rimiere	220	10012	375	
72	Le Val	Seraing	220	45360	400	
73	Marcourt	Rimiere	220	4567	405	
74	Marcourt	Villeroux	220	5887	405	
75	Montlez Houffalize	Villeroux	220	6994	510	
76	Rimiere	Seraing	220	11467	400	
77	Romsee	Seraing	220	9138	400	
78	Borssele (NL)	Geertruidenberg (NL)	380	17168	946	
79	Eindhoven (NL)	Geertruidenberg (NL)	380	8237	1892	
80	Eindhoven (NL)	Geertruidenberg (NL)	380	8237	1892	
81	Eindhoven (NL)	Geertruidenberg (NL)	380	8237	1892	
82	Eindhoven (NL)	Maasbracht (NL)	380	11885	1892	
83	Eindhoven (NL)	Maasbracht (NL)	380	11885	1892	
84	Lonny (FR)	Mastaing (FR)	380	4236	1715	
85	Lonny (FR)	Moulaine (FR)	380	5267	2577	
86	Lonny (FR)	Moulaine (FR)	380	5267	2577	
87	Avelin (FR)	Lonny (FR)	380	3877	2570	
88	Avelin (FR)	Lonny (FR)	380	3877	2570	
89	Avelin (FR)	Mastaing (FR)	380	15701	1715	
90	Avelin (FR)	Mastaing (FR)	380	4297	496	
91	Avelin (FR)	Mastaing (FR)	380	2589	11499	
92	Avelgem	Gouy	150	1453	400	

Table 6.1: (Continued) Lines used in the numerical model.

# gen	Node	Name Plant	Fuel Type	C_g (€ MWh^-1)	$\overline{q}_g$ (MW)	*f*
1	**Avelgem**	Ruien 3	Conv. Coal	20	152	3
2	**Avelgem**	Ruien 4	Conv. Coal	20	158	3
3	**Avelgem**	Ruien 6	Conv. Coal	20	236	3
4	**Avelgem**	Ruien 5	Conv. Coal + repower.	19	238	3
5	**Avelgem**	Ruien 7	Conv. Coal + repower.	19	95	3
6	**Awirs**	Awirs 4	Conv. Coal	20	124	3
7	**Bruegel**	Deux-Acren	Turbojets	59	18	3
8	**Coo**	Coo I	Pumped Storage	13	474	2
9	**Coo**	Coo II	Pumped Storage	13	690	2
10	**Coo**	Cierreux	Turbojets	59	17	3
11	**Doel 1**	Doel 2	Nuclear	10	393	1
12	**Doel 1**	Doel 4	Nuclear	10	985	1
13	**Doel 2**	Doel 1	Nuclear	10	393	1
14	**Doel 2**	Doel 3	Nuclear	10	1006	1
15	**Drogenbos**	Drogenbos	STAG	18	460	2
16	**Drogenbos**	Drogenbos	Gas Turbine	45	78	3
17	**Drogenbos**	Ixelles	Turbojets	59	18	3
18	**Eeklo Noord**	Brugge Herdersbrug	STAG	18	460	2
19	**Eeklo Noord**	Zedelgem	Turbojets	59	18	3
20	**Eeklo Noord**	Zeebrugge	Turbojets	59	18	3
21	**EekloNoord**	Aalter	Turbojets	59	18	3
22	**Gouy**	Saint-Ghislain	STAG	18	350	2
23	**Gouy**	Amercoeur 2	Conv. Coal	20	127	3
24	**Gouy**	Monceau	Conv. Coal	20	92	3
25	**Gouy**	Plate tail	Pumped Storage	13	143	2
26	**Herderen**	Langerlo 1	Conv. Coal + repower.	19	301	2
27	**Herderen**	Langerlo 2	Conv. Coal + repower.	19	301	2
28	**Izegem**	Harelbeke	Diesel Motor	58	77	3
29	**Izegem**	Noorschote	Turbojets	59	18	3
30	**Jupille**	Monsin	Gas Turbine	45	70	3
31	**LaTroque**	Angleur 1 en 3 (Socolie)	STAG	18	121	2
32	**LeVal**	Seraing	STAG	18	460	2
33	**Massenhoven**	Beerse	Turbojets	59	32	3
34	**Meerhout**	Mol 11	Conv. Coal	20	124	3
35	**Meerhout**	Mol 12	Conv. Coal	20	131	3
36	**Meerhout**	Mol	Gas Turbine	45	30	3
37	**Mercator**	Kallo 1	Conv. Gas	21	261	3
38	**Mercator**	Kallo 2	Conv. Gas	21	261	3
39	**Rodenhuize**	Gent (Ham)	STAG	18	53	2
40	**Rodenhuize**	Gent (Ringvaart)	STAG	18	385	2
41	**Rodenhuize**	Rodenhuize 2	Conv. Fuel	40	129	3
42	**Rodenhuize**	Rodenhuize 3	Conv. Fuel	40	128	3
43	**Rodenhuize**	Rodenhuize 4	Conv. Coal	20	269	3
44	**Rodenhuize**	Gent (Ham)	Diesel Motor	58	71	3
45	**Rodenhuize**	Zelzate	Turbojets	59	18	3
46	**Romsee**	Turon	Turbojets	59	17	3
47	**Tihange**	Tihange 1	nuclear	10	962	1
48	**Tihange**	Tihange 2	nuclear	10	1008	1
49	**Tihange**	Tihange 3	nuclear	10	1015	1
50	**Verbrande Brug**	Vilvoorde	STAG	18	385	2
51	**Verbrande Brug**	Schaerbeek	Turbojets	59	18	3

Table 6.2: Generation units

paper is a Mathematical Program with Equilibrium Constraints. (MPEC's) MPECs are a class of problems which are known to be difficult to solve. (Luo, Pang, Ralph, 1996). This paper uses a pragmatic approach to solve them and smoothes the marginal cost function of the generators.

In the model, marginal costs are defined as

$$\frac{\partial C_g^p(q_g)}{\partial q_g} = C_g \cdot \left[1 - \alpha_g \left(\beta_g + \frac{q_g}{\bar{q}_g} \right)^{-\phi_g} + \alpha_g \left(\beta_g + \frac{\bar{q}_g - q_g}{\bar{q}_g} \right)^{-\phi_g} \right] \tag{6.35}$$

with $\bar{q}_g$ denoting the production capacity of production plant g, and C_g is the marginal cost of generation when 50% of the generation capacity of plant g is used. The parameters $\alpha_g, \phi_g, \beta_g$ are chosen such that generators always choose an internal solution. All this will be at the cost of accuracy concerning the exact value of the marginal cost, but the numerical problem becomes much easier to solve and we will be more sure to find a solution close to the global optimum.

The total generation cost is the integral of the marginal cost function, *i.e.*

$$C_g(q_g) = \int_o^{q_g} \frac{\partial C_g(t)}{\partial q_g} dt \tag{6.36}$$

Plant numbers 8, 9 and 24 are *pumped storage plants*, *i.e.* they can store energy in the form of a water reservoir. When generation costs are low, these plants consume electricity and pump water to a higher level. When generation costs are high, the reservoir is emptied and electricity is produced. The underlying decision process is not modelled in this paper. We assume that these plants generate electricity during peak periods at a marginal cost of 7€ per MWh, and we count them as part of the consumption side during the off-peak periods.[12]

Figures 6.2 and 6.3 show the aggregate supply function of the generation plants with and without the storage plants included. The stepped function is the real supply function, while the more or less fluent line is the approximated supply function. The approximation is reasonably close to the real supply function, for values of demand above 6 GW.

6.4.3 Electricity demand

The model has been calibrated on the basis of Belgian data for electricity demand in 2002[13]. In that year the average demand was 9.52 GW. Total yearly demand in Belgium is 83.4 TWh per Year. Figure 6.4 presents a

[12] A better modelling of the pumped storage plants would require to take into account the capacity constraint of the water reservoir, and to make the decisions of whether to consume or to generate endogenous.

[13] The network of one part of Luxembourg forms an integral part of the Belgian network. Demand levels for that part are included in the model here.

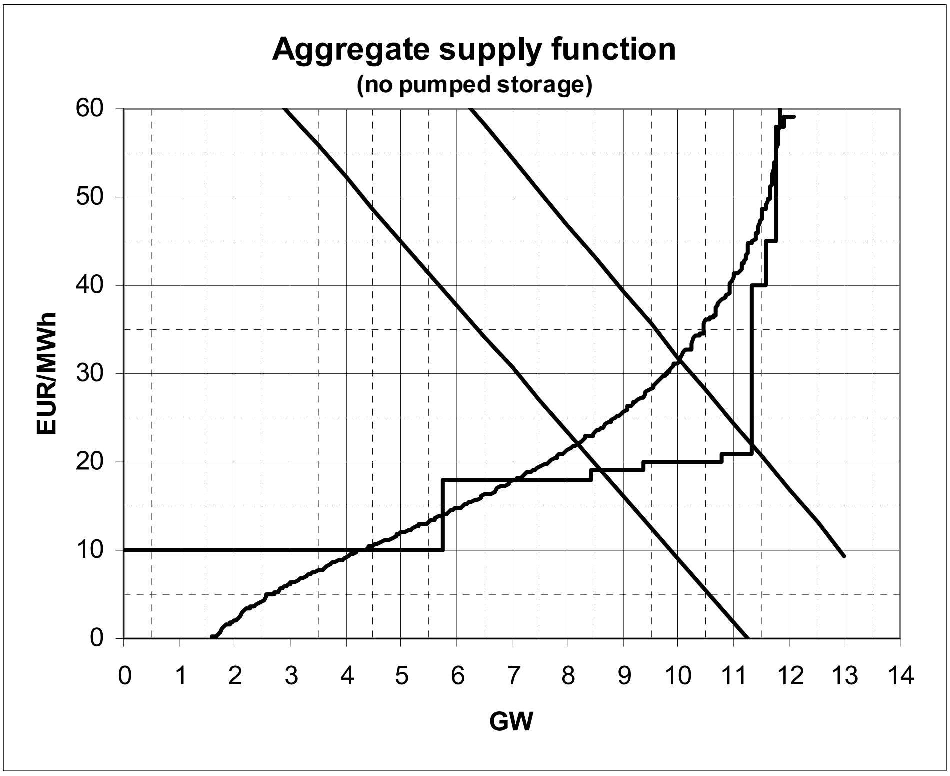

Figure 6.2: Aggregate supply function excluding pumped storage.

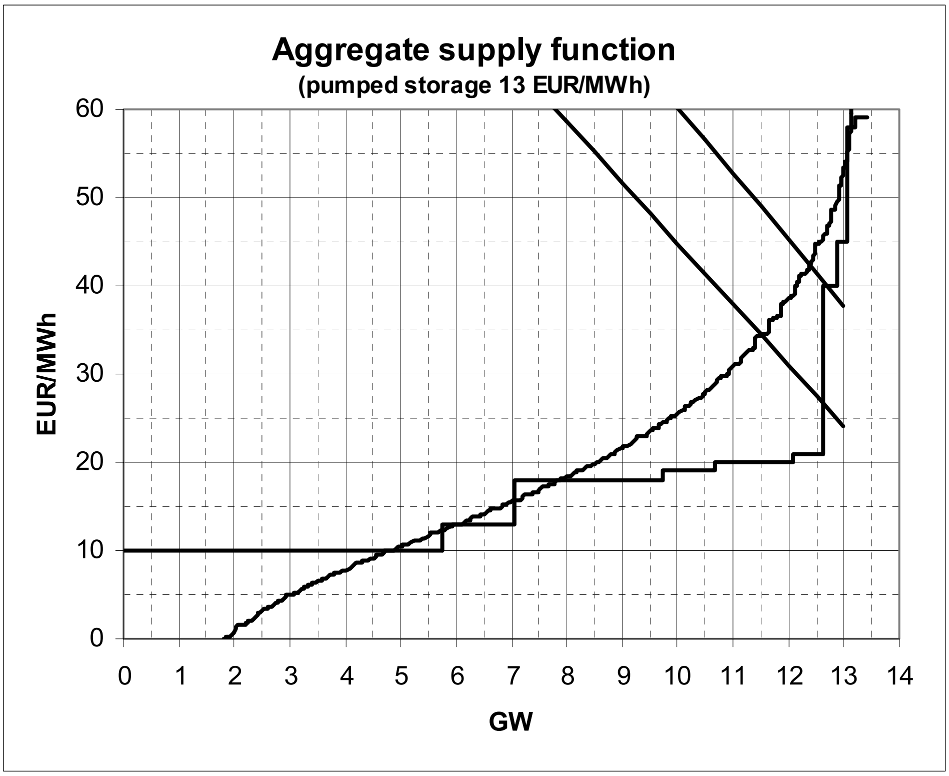

Figure 6.3: Aggregate supply function including pumped storage.

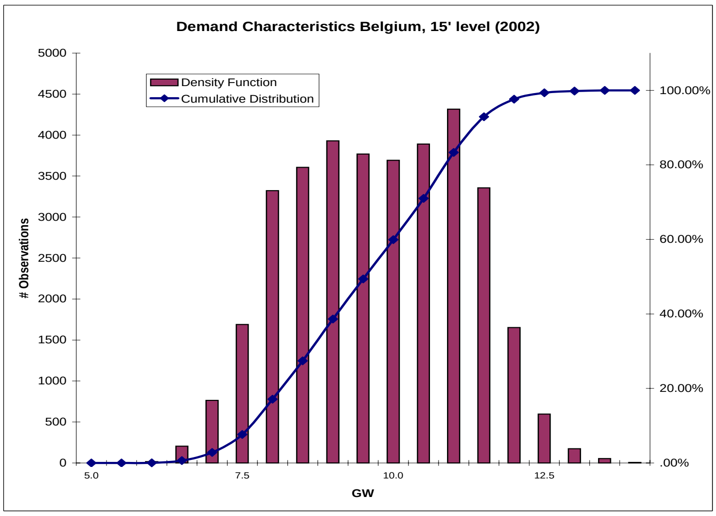

Figure 6.4: Histogram of electricity demand in Belgium in 2002. (Source ELIA)

histogram of demand in Belgium. The histogram is based on periodical observations with a length of 15 minutes. The highest and lowest observed demand levels were 13.7 GW and 5.8 GW, respectively.

Extending the model from one period to multi periods Obviously, the demand for electricity is not constant over time and in order to take this into account, the numerical one-period model has been extended to a 4-period model. For this, the model needs to be slightly extended, as one time period might have an effect on other time periods. In the present model, we distinguish three potential links.

First, cross-substitution can take place between time periods. For example, demand for electricity during the night will not only depend on the price in the night, but also on the price that is charged during the day. In this model it is assumed that these cross-substitution effects are zero. There is thus no intertemporal substitution.

Second, as was mentioned before, the consumption and generation decision of the pumped storage plants can be endogenized. And finally, when the transmission firm is maximizing welfare subject to a budget constraint, then this budget constraint creates a link between the different time periods. The marginal welfare cost of obtaining revenue for the network operator should now be equal over each time period.

Note that, if the network operator maximizes profit, then there is no (binding) budget constraint and the different time periods can be considered independently given the assumptions with respect to the two potential links

Period	Demand Observed (GW)	Period Length	Demand Model (GW)	Reference Price [€/MWh]
1	12.5	2.4%	12.0	45.2
2	11.5	20.1%	11.0	37.9
3	10.0	38.9%	9.5	35.6
4	8.0	38.6%	7.5	27.0

Table 6.3: Calibration of the 4 time periods

discussed above.

6.4.4 Network operator

The network operator has total costs of B =649 M€ per year (Source: Annual report ELIA, 2002). Capital costs are about 50% of the total costs, the other 50% being operating costs, such as wages and network maintenance costs. Wages and network maintenance costs are not directly related to the amount of MW transported over a line, they are inherent to the existence of that line. Therefore, as we could not find a more detailed description of the cost function of the network operator, we assume all costs to be fixed. Network losses are neglected in the model. Clearly, these would depend on the actual use of the network. With a total electricity demand of 83.4 TWh per year, the average cost of the network operator is 7.78€ per MWh.

6.4.5 Calibration

The calibration of the model involves three steps. Each of these three steps is described below.

Fixing periodic aggregate demand and the length of each period. The first step is to decide about the level of electricity demand in each of the four periods, and about the length of each period in a standard year. This has been done on the basis of the data presented in Figure 6.4. This figure shows how often a certain demand level occurs in the Belgian market. We will consider 4 periods with average demand levels fixed at 8, 10, 11.5 and 12.5 GW. The length of each time period is then set such that the cumulative distribution function of the 4 periods approximates the observed cumulative distribution function (Table 6.3). As 500 MW of this demand is provided by small generators, the demand level as seen by the generators in our model is fixed 500 MW lower. Thus, the demand levels used to calibrate the demand functions are 7.5, 9.5, 11 and 12 GW.

Fixing a reference price for each period. Given the periodic electricity demand, derived in the first step, we minimize the production costs to supply this demand. Here, it is assumed that pumped water storage can only be

# Cons	Node	MWh
1	Gouy	780
2	Lint	746
3	Verbrande Brug	690
4	Bruegel	661
5	Zandvliet	618
6	Gramme	579
7	Izegem	526
8	Meerhout	508
9	Tergnee	471
10	Massenhoven	432
11	Seraing	378
12	Lixhe	350
13	Belval	341
14	Mercator	329
15	Achene	286
16	Awirs	281
17	Champion	254
18	Rimiere	229
19	Aubange	226
20	Jupille	223
21	Romsee	165
22	La Troque	125
23	Rodenhuize	123
24	Avelgem	116
25	Villeroux	95
26	Montlez Houffalize	94
27	Drogenbos	84
28	Marcourt	83
29	Heinsch	60
30	Harnoncourt	57
31	Eeklo Noord	34
32	Brume	25
33	Saint Mard	14
34	Latour	14

Table 6.4: Distribution of demand over the different nodes when total demand is 10 000 MW

used in period one and two. In the periods three and four, pumped storage plants pump water into a water reservoir.

Via this procedure, we obtain the marginal production cost for each period. The obtained values are increased with the average costs of the network operator (7.78 € per MWh) to obtain a reference price for each period (Table 6.3).

Fixing periodic electricity demand in the consumption nodes In the third step, we derive for each node a linear demand function. The price elasticity of demand is assumed to be -0.5 in all nodes and all periods. Total demand is distributed proportionally over the different periods on the basis of the data in Table 6.4 and the reference prices calculated in step 2[14]. This information is sufficient to derive for each consumption node the parameters of the linear demand function.

[14]Data is based on Van Roy (2001).

The Netherlands		
Node		**[MW]**
Maasbracht (NL)		-731
Geertruidenberg (NL)		-368
Borssele (NL)		99
	TOTAL	**-1000**
France		
Node		**[MW]**
Aveli (FR)		543
Lonny (FR)		34
Moulaine (FR)		423
	TOTAL	**1000**

Table 6.5: Exogenous generation levels at the foreign nodes. Negative numbers are loads.

6.4.6 Transit

It was already mentioned that the technical features and the dimension of the grid are inspired by the Belgian electricity market. Also, the generation and demand characteristics are based on data for Belgium. Therefore, we also take into account in our model that the Belgian grid is used for relatively large transit flows. These flows are generally directed from France to The Netherlands and, as a first approximation, we impose an exogenous transit flow of 1000 MW from the south to the north. This transit is assumed to occur in all periods. The foreign generation and load nodes are summarized in Table 6.5.

Import from France to Belgium is neglected. Without modelling the French generator(s), import cannot be included in our model in a sound way. Import is about 400 MW.

Clearly, this is only an approximation. A more detailed and better modelling procedure should be the subject of further research.

6.5 Simulation results

This section discusses some simulation results obtained with the model. However, before starting the discussion, we first try to grasp some intuition on the setting of and relation between the transmission charges for consumers and generators. Then, in *subsection 2*, we discuss the simulation results obtained in a one period model, under the assumption that

- demand is low;
- the transmission firm maximizes welfare (with budget constraint (second best) and without (first best));
- the generation market is perfectly competitive;

- security constraints are neglected.

Subsection 3 then discusses simulation results obtained under the same assumptions except that now a high demand is assumed. *Subsection 4* discusses the same scenario's as in subsection 3, but now the $n-1$ rule is imposed as a security of supply constraint.

Finally, *subsection 5* introduces the multi-period approach, considers alternative objective functions for the transmission company and alternative market structures for electricity generation. The impact of these alternatives on the market outcome will be discussed.

One final remark has to be made. The simulations presented in this paper serve the purpose of illustrating the possibilities of the model. The current simulation results do not pretend to give a fully realistic view of what would be the outcome for the Belgian electricity market if the liberalization process is finalized. But we do feel that the model has the potential to provide insight in the consequences of such structural and regulatory changes. However, this would require a more detailed modelling, especially of the regulatory settings.

6.5.1 Interpreting transmission prices

In the current model, we assume that the network operator is able to set a transmission price for generation and consumption in each node: τ_i^p and τ_i^c. Within the set of linear price structures, this is the most general assumption. It encompasses a number of 'price structure' options as special cases. For example, only charging consumption, only charging generation, a separate but uniform tariff for generation and consumption and, one uniform tariff for both generation and consumption as the most extreme case. In the simulations presented in this paper, we stick to the most general case which means that the network operator has the freedom to set differentiated charges for generation and consumption.

However, the optimal transmission charges are not uniquely defined. First, take a node i at which no consumers are connected. For that node, the consumer transmission price τ_i^c does not play a role and it can safely be set equal to zero. The same is true for nodes without generation. Here, τ_i^p is not uniquely defined and the charge is set equal to zero.

Second, note that a firm generating electricity in node i, that is sold in node j, has to pay a per unit transmission charge equal to

$$\tau_{ij} = \tau_i^p + \tau_j^c$$

For the generation firm, only the total transmission charge is important, not its exact composition. The network operator has therefore one degree of freedom in setting the transmission charge components. This can easily be checked from the equations 6.19 and 6.20, and by noting that one can uniformly increase all generation tariffs with t and decrease all consumer tariffs with t without changing the sum of the charges. Indeed, the new tariffs τ_i^{c*} and τ_i^{p*} will equal

$$\begin{aligned}\tau_i^{c*} &= \tau_i^c - t\\ \tau_i^{p*} &= \tau_i^p + t\end{aligned}$$

but the total charge for transmission between any two nodes i, and j remains the same, *i.e.* $\tau_{ij} = \tau_{ij}^*$. We can therefore arbitrarily fix the consumers' transmission price in one node equal to zero. This is done for the consumption charge in the swing node:

$$\tau_i^c = 0 \qquad i = \text{swing node}$$

Finally, note that the model implicitly assumes that the charges need to be paid for all consumption and generation, even if generation and consumption is located at the same node. A generator in node i who sells electricity locally does not use the transmission network, but will have to pay a transmission payment $\tau_{ii} = \tau_i^c + \tau_i^p$. We will call this charge the price wedge, because this charge creates a wedge between the consumer price and the generator price in node i[15].

The next subsection continues with a discussion of the simulation exercises.

6.5.2 Low demand - No security of supply constraints

This simulation scenario assumes low demand (off-peak), no security of supply considerations and welfare maximizing behavior at the side of the network operator. Due to the low demand assumption, congestion is not an issue. The results can be interpreted as being the results for running the electricity system in an off-peak period of one hour.

Two scenarios are compared, the *first best* and the *second best*. In the *first best* scenario, competition in the generation market is perfect and the network operator maximizes welfare *without* facing a budget constraint. The *second best* scenario is identical to the first best scenario except that now the network operator maximizes welfare subject to a budget constraint.

It is assumed that the network operator needs to obtain the same revenue in each hour of the year, that is 74 087 (= 649 M€ / 8760 h) € per *hour*. In subsection 5 this assumption will be relaxed when we use the 4-period model.

Table 6.6 shows the simulation results for the *first best* and the second best cases in terms of welfare, surpluses for the economic agents, the network operator costs, generation (and consumption) level and the multiplier of the budget constraint. Quantities are expressed in MW, but since the simulations

[15] With imperfect competition, the generator price is not defined.

Low Demand	**1st Best**	**2nd Best**	***Rel. Change***
Welfare (k€/hr)	287	**282**	*101.6%*
Consumer Surplus (k€/hr)	243	**193**	*126.4%*
Producer Surplus (k€/hr)	117	**89**	*131.3%*
Profit Network Operator (k€/hr)	-74	**0**	-
Revenue Network Operator (k€/hr)	0	**74**	*0.0%*
Fixed Cost Network Operator (k€/hr)	74	**74**	*100.0%*
Multiplier Budget constraint (€/€)	0.000	**0.149**	-
Total Consumption (MWh/hr)	8223	**7315**	*112.4%*

Table 6.6: Period 4: Low demand without n-1 security constraints

cover a 1 hour period, they can also be interpreted as MWh. Monetary values are expressed in million euro per hour.

In the first best scenario, generation is equal to 8 223MW. Consumer and producer surpluses are 243 k€ and 117 k€, respectively. Aggregate welfare, being the sum of these values and the surplus generated by the network operator -74 k€ equals 287 k€.

Congestion on the grid is not an issue in this simulation and, therefore, the transmission charges for consumption and generation are set equal to zero, *i.e.*

$$\tau_i^p = \tau_i^c = 0$$

The network operator is maximizing welfare and setting non-zero transmission charges would create distortions without any need. As transmission is for free, there will be a uniform end-user price for electricity in the Belgian market.

In the *second best* case, the network operator will set non-zero transmission charges to obtain sufficient revenue to cover his costs. Standard Ramsey pricing will be used to obtain this revenue. Transmission charges (τ_i^c, τ_i^g) are set inversely proportional to the demand, resp. supply elasticity in each node[16]. The total deadweight loss in the market is minimized. Compared with the first best, the distortions in the reference scenario create a total welfare loss of 1.6%. At the margin, generating 100 € extra revenue for the network operator creates a deadweight loss of 14.9 €.

In this second best scenario, the end user prices will generally be higher than in the first best case. As a result, demand and generation (7 315MW) will be lower than in the first best case (8 223MW) . Higher end user prices imply a lower consumer surpluses, but also the surplus of the generators (their profit) reduces due to the transmission charges.

[16]Because demand is linear and, by construction, has the same intercept in all nodes, elasticities are identical in each node. As a consequence, all consumers face the same consumer charge.

The level and shapes of the marginal generation cost functions are different and therefore, different charges are set at different nodes.

High Demand	**1st Best**	**2nd Best**	***Rel. Change***
Welfare (k€/hr)	865	**864**	*100.1%*
Consumer Surplus (k€/hr)	581	**556**	*104.5%*
Producer Surplus (k€/hr)	352	**308**	*114.2%*
Profit Network Operator (k€/hr)	-68	**0**	-
Revenue Network Operator (k€/hr)	6	**74**	*8.5%*
Fixed Cost Network Operator (k€/hr)	74	**74**	*100.0%*
Multiplier Budget constraint (€/€)	0.000	**0.025**	-
Total Consumption (MWh/hr)	12413	**12146**	*102.2%*

Table 6.7: Period 1: High demand without n-1 security constraints.

6.5.3 High demand - No security of supply constraints

This subsection compares the first best and the second best in the case of high demand. It neglects the $n-1$ security constraints. These constraints will be added in the next subsection.

If the network operator would set all transmission charges equal to zero in the *first best*, then the network capacity would be insufficient to satisfy the demand for transmission. Thus, congestion is an issue. Therefore, the network use must be charged in order to solve capacity problems. The charges should be chosen such that distortions are minimized. The best way to do this is to tax the effective use of the network, but not the 'intra-nodal' trade, *i.e.* the network operator will set the price wedge equal to zero, *i.e.* $\tau_{ii} = 0$ $(\tau_i^c = -\tau_i^p)$. The reason for this is simple: setting a positive price wedge $\tau_{ii} = \tau_i^c + \tau_i^p > 0$, increases the distortion in the local market at node i, but only has an indirect effect on the network flows that cause the congestion. Therefore, it is best to set the price wedge equal to zero. Note that this only makes sense for nodes at which both generators and consumers are connected. Otherwise the price wedge does not play a role.

These congestion charges allow the network operator to collect a revenue equal to 8.5 percents of the fixed costs (Table 6.7). In the *second best* case, the network operator needs to increase transmission charges from their first best level, in order to obtain sufficient revenue for the remaining 91.5% (= 100% − 8.5%) of his budget.

Note that the impact of adding the budget constraint (*second best* versus *first best*) on welfare and on the distribution of the surpluses is relatively small compared to its impact in the 'low-demand' scenario. The reason is that, in this scenario, congestion occurs in the fist as well as in the second best case. Once congestion is 'solved', the additional distortions resulting from setting transmission charges that satisfy the revenue constraint are small.

6.5.4 High Demand - With security of supply constraints

In this scenario, $n-1$ security constraints are added. The results are shown in Table 6.8.

High Demand - Contingency	1st Best	2nd Best	*Rel. Change*
Welfare (k€/hr)	856	**856**	*100.0%*
Consumer Surplus (k€/hr)	563	**554**	*101.7%*
Producer Surplus (k€/hr)	316	**301**	*105.0%*
Profit Network Operator (k€/hr)	-24	**0**	-
Revenue Network Operator (k€/hr)	50	**74**	*67.5%*
Fixed Cost Network Operator (k€/hr)	74	**74**	*100.0%*
Multiplier Budget constraint (€/€)	0.000	**0.010**	-
Total Consumption (MWh/hr)	12141	**12044**	*100.8%*

Table 6.8: Period 1: First best vs. Second best, Security constraints included.

First Best - High Demand

IF this line breaks		**THEN this line at limit**		**Shadow Price**
From	To	From	To	[€/MW]
Aubange	Moulain (FR)	Aubange	Brume	20.3
Doel 2	Mercator	Doel 2	Zandvliet	4.7
Jupille	Lixhe	Gramme	Rimiere	19.3
LeVal	Seraing	Herderen	Lixhe	53.3

Table 6.9: Congested lines in the first best model

Compared to the previous simulation exercise, the available transmission capacity has reduced, thus congestion will be a larger issue than it was in section 3. However, on the basis of a comparison of these two scenarios, its impact seems to be rather limited. The *first best*, transmission charges will on average be higher in order to solve the congestion problem, but apparently the charges have been changed primarily in a way that reshuffles generation (and consumption) over the network without reducing total production. The network operator's revenue via congestion charges is now sufficient to cover 67.5% of the costs. As revenue generation is not an objective for the network operator in the first best case, he still minimizes distortions and sets $\tau_i^p = -\tau_i^c$

In the *second best* case, the network operator increases transmission prices from their first best level, to cover the remaining 32.5% (= 100% − 67.5%) of his costs.

Table 6.9 and 6.10 show which lines are binding under the two scenarios. If the line in the first column breaks down, the line in the second column will be loaded up to its thermal capacity. The last column shows the shadow price of the thermal constraint of the lines that become constrained.

It should be noted that the results largely depend on the assumed distribution of demand and better information is needed in order to get a more realistic prediction about congestion in practice. However, these simulations clearly illustrate that the $n-1$ security constraints are important in analyzing congestion.

The simulations discussed so far were intended to illustrate the impact of demand and of $n-1$ security constraints on the market outcome and on transmission charges. The next subsection goes one step further and introduces a multi-period setting, and alternative assumptions on the behavior of the generation and the network operator.

Second Best - High Demand

IF this line breaks		THEN this line at limit		Shadow Price
From	To	From	To	[€/MW]
Aubange	Moulain (FR)	Aubange	Brume	19.4
Doel 2	Mercator	Doel 2	Zandvliet	2.9
Jupille	Lixhe	Gramme	Rimiere	19.3
LeVal	Seraing	Herderen	Lixhe	52.6

Table 6.10: Congested lines in the second best model

The congestion is in other locations than in Van Roy (2001). He found congestion on the 150 kV network due to local over-production in the region Herderbrug – Rodenhuize. There are three reasons why the results are different:

1. We assume a constant demand distribution over the nodes of network for all time periods. Van Roy models the distribution of demand more detailed;
2. Our model does not include the 150 kV transmission lines;
3. Van Roy assumes that production levels are exogenous, while they are exogenous in our model.

6.5.5 A multi-period setting with strategic behavior of generators and the transmission firm

We consider 6 scenarios. For the network operator we evaluate two assumptions with respect to his objective function: welfare maximization subject to a budget constraint (index *'W'*), and profit maximization (*'P'*). For the generation market structure we evaluate three assumptions: perfect competition (*'PC'*), Cournot competition (*'CO'*), and monopoly (*'MO'*). The scenario *W - PC* is in fact the second best scenario discussed in subsection 4, except that now 4 periods are considered. Therefore, the simulation results are not immediately comparable. We will also report the results of the first best scenario, *i.e.* welfare maximization without a budget constraint. All simulations were made with the 4-period model and include the $n-1$ security constraints.

Table 6.11 presents the consumers surplus, generation profit, the revenue, the fixed costs, and the profit of the network operator, welfare and total generation for each scenario. In the scenarios with welfare maximization subject to a budget constraint, the multiplier of this constraint is also shown.

The results do not come as a surprise. Ceteris paribus, regulating the network operator and increasing competition in generation increases welfare.

The multiplier of the budget constraint of the network operator measures the net cost of giving one Euro to the network operator. The effect is about ten times as large with monopoly than with perfect competition. The reason

All Periods - Contingency	1st . Best	W - PC	W - CO	W - MO	P - PC	P- CO	P - MO
Welfare (M€/yr)	4031	**4012**	3648	2920	2947	2334	1725
Consumer Surplus (M€/yr)	3047	**2708**	1643	828	847	503	271
Producer Surplus (M€/yr)	1622	**1304**	2006	2093	444	699	760
Profit Network (M€/yr)	-638	**0**	0	0	1656	1132	694
Revenue Network (M€/yr)	11	**649**	649	649	2305	1781	1343
Fixed Cost Network (M€/yr)	649	**649**	649	649	649	649	649
Multiplier Budget Network (€/€)	0.000	**0.070**	0.373	0.706	0.000	0.000	0.000
Total Consumption (GWh)	84,998	**80,120**	62,258	44,178	44,676	34,374	25,252

Table 6.11: Aggregate results of the 6 scenarios.

All Periods - Contingency	1st . Best	W - PC	W - CO	W - MO	P - PC	P- CO	P - MO
Welfare (%)	100.49	**100.00**	90.94	72.79	73.46	58.17	43.00
Consumer Surplus (%)	112.53	**100.00**	60.66	30.56	31.30	18.58	10.00
Producer Surplus (%)	124.39	**100.00**	153.83	160.50	34.02	53.58	58.30
Profit Network (-)	-	**-**	-	-	-	-	-
Revenue Network (-)	1.75	**100.00**	100.00	100.00	355.13	274.39	206.94
Fixed Cost Network (%)	100.00	**100.00**	100.00	100.00	100.00	100.00	100.00
Multiplier Budget Network (-)	-	**-**	-	-	-	-	-
Total Consumption (%)	106.09	**100.00**	77.71	55.14	55.76	42.90	31.52

Table 6.12: Relative performance of the 6 scenarios. The Second Best situation (W - PC) is used as a reference.

for this is that in the monopoly case the distortion in the electricity market is already high, and obtaining extra revenue will increase this distortion even more.

Table 6.12 shows the same results as Table 6.11, but now they are expressed relative to the second best scenario.

What is the effect of regulating the network operator under the three alternative market structures for generation? Table 6.13 shows the effect of introducing perfect regulation of the network operator. Under perfect competition regulation increases welfare with 1 065 M€. The profit of the network operator reduces with 1 656 M€ and the consumers and the producers gain 1 860 M€ and 860 M€ respectively. Total generation increases with 35.4 TWh.

From the table we can learn that regulation increases welfare, and is most effective when there is Cournot competition in generation, and least effective if there is perfect competition. Regulation decreases the profit of the network operator. Generators and consumers share the increase in welfare. The

All Periods - Contingency	PC	CO	MO
Welfare (M€/yr)	1065	1315	1195
Consumer Surplus (M€/yr)	1860	1139	557
Producer Surplus (M€/yr)	860	1307	1332
Profit Network (M€/yr)	-1656	-1132	-694
Revenue Network (M€/yr)	-1656	-1132	-694
Fixed Cost Network (M€/yr)	-	-	-
Multiplier Budget Network (€/€)	-	-	-
Total Consumption (GWh)	35444	27884	18926

Table 6.13: Effect of regulation, for the three generation market structures.

sharing depends on the market structure of the generation market. In the monopoly case, the fruits of regulation go mainly to the monopolist. With perfect competition, the welfare gains go mainly to consumers.

Congestion in the network In the multi-period model, both the first best and the second best scenario have congestion in the peak period. In the other periods, demand for transmission is too low and there is no congestion.

6.6 Conclusions

This paper sets a first step in understanding the strategic behavior of a network operator via a numerical simulation model. It looks at the pricing behavior of the network operator in a market with transmission constraints and with imperfect competition in generation. Consumers are assumed to be price takers in the electricity market. Generators are Cournot players in production and sales, but they are price takers in the transmission market. The network operator is a Stackelberg leader and sets the transmission price before the generators decide about their production and sales.

The model is illustrated with some simulation runs. The parametrization of the model is inspired by the technical characteristics of the Belgian electricity system. It includes the Belgian high voltage transmission grid, and the most important lines in France and the Netherlands. The network is presented as a linearized DC-load flow model. Transmission is limited by the thermal constraints of the lines and $n-1$ security constraints are imposed. If one of the lines breaks down, then the remaining lines should be able to transport the electricity.

The model studies 6 scenarios. It assumes a perfectly regulated network operator who maximizes welfare subject to a budget constraint, and a non-regulated network operator who maximizes profit. For the generation sector, it considers 3 market structures: Perfect competition, Cournot competition, and a monopoly market.

Imperfect competition and a badly regulated transmission network both have the expected impact on welfare: they reduce it. (Perfect) regulation of the network operator has the largest impact if there is Cournot competition in generation and the smallest if the generation sector is competitive.

The paper illustrates that $n-1$ security constraints should be modelled if one wants to have an idea of the amount of congestion in the network.

The simulations presented in this paper are only intended to illustrate the possibilities of the model. In its current form, and eventually with some extensions, the model can be used to study many relevant policy issues concerning electricity markets. We give a short non-exhaustive survey of possible extensions and applications.

The ownership structure and the location of the firms in the grid might be important in determining the market power of the generators. If firms have geographically dispersed production capacities, the effect of congestion might be much smaller than when each firms is geographically concentrated.

Belgium is located between a low priced country (France) and the high price country (the Netherlands) and it serves as a transit country. The model in the paper, could be used to calculate the welfare impact of different levels of transit.

As most of the congestion on the Belgian network involves international transactions it would be interesting to also include the Dutch, the German, and the French generation markets and networks, as in Hobbs *et al.* (2002).

Consumers do not resell electricity and there is no arbitrage in the model. This could be included and its impact could be studied. Appendix 6.A shows how arbitrage can be introduced in the model.

In the paper, we assumed that the generators are competing à la Cournot. A possible extension is to assume that generators compete with conjectured supply functions, as shown in Hobbs, Metzler, Pang (2000) and in Day Hobbs, Pang (2002).

The paper considers two extreme forms of regulation: no regulation and perfect regulation. Other types of regulation could be introduced. For example, the regulator could fix the average price over nodes and time periods while leaving the decisions about the (linear) tariff structure to the network operator. The model can also be used to study the welfare impact of alternative tariff structures, such as for example postage stamp tariffs.

To improve the modelling of the behavior of the network operator, his cost function should be specified as a function of the use of the transmission network and should allow for new investments in transmission lines. A welfare maximizing network operator might invest in more transmission capacity to increase competition in the generation market. A model for the regulation of the network operator can then also be based upon his costs.

Appendix 6.A Arbitrage

The model of Smeers and Wei (1997) has been extended by Metzler *et al.* (2003) and Hobbs (2001) to include arbitrage. This appendix shows how arbitrage is introduced in the model presented in this paper.

An arbitrageur can be modelled as an extra generator with index $a \in F$ who has no generation capacity $G_a = \varnothing$, and who is price taker in both the energy and the transmission market.

The arbitrageur maximizes

$$\max_{s_{ai}} \Pi^{arb} = \sum_{i \in I} (p_i - \tau_i^c) \cdot s_{ai}$$

Subject to:

$$\sum_{i \in I} s_{ai} = 0 \qquad (\lambda_a^p) \tag{6.37}$$

The first order conditions of the arbitrageur are the following:

$$(p_i - \tau_i^c) = \lambda_a^p \quad \forall i \in I \tag{6.38}$$

With arbitrage, the price difference between two nodes need to be equal to the differences in congestion charges for consumers.

$$(p_i - p_j) - \left(\tau_i^c - \tau_j^c\right) = 0 \tag{6.39}$$

Intuition: If the price p_i is too high, arbitrageurs will buy electricity from consumers in region j. The value of this electricity for consumers in node j is p_j. If consumers reduce consumption, they will save τ_j^c on their transmission bill. They will sell their electricity thus for a price $p_j - \tau_j^c$. The arbitrageur will sell the electricity to consumers in region i at a price $p_i - \tau_i^c$. The consumers in region j have to pay the congestion charge before consuming.

7

How much should the network operator tell about the state of the network?

It is often claimed that the operator should disclose all his information on the state of the network. This paper shows that it is not always true if a generator has market power. Better information allows the generator to use his market power more efficiently, decreasing total surplus.

7.1 Introduction

Several countries liberalized their electricity industries. One of the main ideas is to organize competition in the generation of electricity. Economies of scale in generation are assumed to be sufficiently small to have a more or less competitive generation market. The technical complexities in the network require central coordination by a network operator. Given his natural monopoly the network operator has to be regulated.

In the liberalized market, an electricity service is seen as a bundle of different goods: energy and transmission. Energy is traded in the energy market. It is sold by generators and bought by consumers. Transmission is provided by the network operator, and bought by consumers and generators.

One of the problems in organizing electricity markets is the strong interlinkage of the market for energy and the market for transmission. Wilson (2002) discusses some of those problems.

This paper looks at one aspect of the interlinkage of both markets: How should the network operator share his information with the generators and the consumers?

It is often claimed that the network operator should disclose all his information on the state of the network in order to increase total surplus in both markets. This paper shows that this is not always true if a generator has market power. Better information allows the generator to use his market power more efficiently, decreasing total surplus.

7.2 Model

The model represents the electricity sector in a simplified form. We assume that network capacity is stochastic and depends on the state of nature $\theta \in \{\theta_H, \theta_L\}$. In state θ_H, network capacity is large; in state θ_L it is low. The probability of state θ_H is p_H and of state θ_L it is p_L.

There is one dominant generator who behaves strategically, all other players are price takers. The generator can chose to behave (B) or misbehave (M). Table 7.1 gives the pay-off of the generator in state θ, when he chooses B or M. Behaving is optimal when the capacity of the transmission capacity is large, $\Delta X = X - x \geq 0$; misbehaving is optimal when the capacity is small, $\Delta Y = Y - y \geq 0$.

	B	M
θ_H	X	x
θ_L	y	Y

Table 7.1: Pay-off of the generator

The underlying story could go as follows: There are two regions. In region A there is perfect competition in generation, in region B there is a monopolistic generator. A network connects both regions. In state θ_H the capacity of the network is high. The monopolist in region B cannot use his monopoly power to drive up prices, as the consumers would buy electricity in region A. It is optimal for him to behave (B). In state θ_L, transmission capacity is low, and the monopolist strategically drives up prices for electricity in region B. He misbehaves (M).

The network operator maximizes total surplus. He always prefers the generator to behave. His pay-offs are given in Table 7.2 with $\Delta C = C - c \geq 0$ and $\Delta D = D - d \geq 0$.

	B	M
θ_H	C	c
θ_L	D	d

Table 7.2: Pay-off of the operator

The timing of the game is as follows:

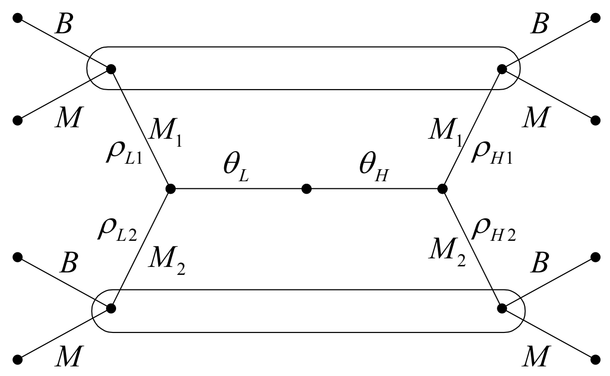

Figure 7.1: Graphical presentation of the message game.

- Stage (-1) The network operator announces a certain disclosure strategy. The disclosure strategy specifies how much information he will share with the monopolist in stage (1)(see below).
- Stage (0) Nature draws a state θ, which is learned by the network operator.
- Stage (1) The network operator discloses information to the generator, according to his disclosure strategy.
- Stage (2) The generator chooses to behave (B) or misbehave (M)

The disclosure stage in stage (1) is a message game: the operator sends a message $M \in \{M_1, M_2\}$ to the generator. He can choose between message M_1 and M_2. In the most general case he uses a mixed strategy. In state θ_H he sends message M_1 and M_2 with probability ρ_{H1} and $\rho_{H2} = 1 - \rho_{H1}$. In state θ_L with probability ρ_{L1} and $\rho_{L2} = 1 - \rho_{L1}$.

The game is presented in the Figure 7.1.

Given the disclosure strategy of the operator, the generator updates his beliefs using Bayes rule. Define $\mu(M)$ the ex-post belief of the generator that θ_H occurred when he receives the message M.[1]

$$\mu(M_1) = P(\theta_H \,|M_1\,) = \frac{P(\theta_H, M_1)}{P(M_1)} = \frac{p_H \rho_{H1}}{p_H \rho_{H1} + p_L \rho_{L1}} \tag{7.1}$$

$$\mu(M_2) = P(\theta_H \,|M_2\,) = \frac{P(\theta_H, M_2)}{P(M_2)} = \frac{p_H \rho_{H2}}{p_H \rho_{H2} + p_L \rho_{L2}} \tag{7.2}$$

The disclosure technology includes a whole range of strategies. The network operator can disclose all his information by setting ($\rho_{H1} = 1$ and $\rho_{L1} = 0$). The generator has then perfect information $\mu(M_1) = 1$ and $\mu(M_2) = 0$.

[1]Believe μ is a function which assigns to each message a probability, $\mu : \{M_1, M_2\} \longmapsto [0, 1]$.

He can as well hide all information by setting $\rho_{H1} = \rho_{L1}$, in which case the generator has the same ex-post and ex-ante beliefs: $\mu(M_1) = \mu(M_2) = p_H$.

The optimal action of the generator depends upon his belief μ. If he behaves (B), he expects to receive the profit

$$\mu X + (1 - \mu)y \tag{7.3}$$

If he misbehaves (M), he expects to receive profit

$$\mu x + (1 - \mu)Y \tag{7.4}$$

The generator is indifferent between behaving and misbehaving when he believes that the probability for state θ_H is K

$$\mu = K \equiv \frac{\Delta Y}{\Delta X + \Delta Y} \tag{7.5}$$

If the generator believes that the probability is higher $\mu \geq K$, he will behave (B). If he believes it is lower $\mu(M) < K$, he will misbehave (M).

Given the belief of the generator $\mu(\cdot)$, the expected pay-off of the operator at stage (-1) W, is as follows:[2]

1. If $\mu(M_1) \geq K$ and $\mu(M_2) \geq K$ the operator receives $W_1 = p_H C + p_L D$
2. If $\mu(M_1) \geq K$ and $\mu(M_2) < K$ he receives $W_2 = p_H(\rho_{H1}\Delta C + c) + p_L(\rho_{L1}\Delta D + d)$
3. If $\mu(M_1) < K$ and $\mu(M_2) < K$ he receives $W_3 = p_H\, c + p_L\, d$

In W_1 the generator always behaves, in W_2 the generator sometimes behaves and sometimes not, in W_3 the generator always misbehaves. It is clear that $W_1 > W_2 > W_3$.

7.3 Network operator can commit

Let us assume that the operator can commit to the disclosure strategy chosen in stage (-1).

The network operator chooses ρ_{ij} in order to maximize his objective W. A particular choice of ρ_{ij} will lead to believe $\mu(\cdot)$ and an expected level of welfare W.

$$\rho_{ij} \underset{-}{\longrightarrow} \mu(\cdot) \longrightarrow W \tag{7.6}$$

The profit of the network operator W is a discontinuous function of the disclosure strategy ρ_{ij}.[3] It can be shown that the optimal strategy of the network operator is as follows:

[2] We assume that the generator will behave when he is indifferent. That is a standard assumption in the Principle-Agent literature.

[3] The disclosure strategy ρ_{ij} is a vector $\{\theta_{H1}, \theta_{H2}, \theta_{L1}, \theta_{L2}\}$ which specifies the probability to send M_i in state θ_j.

If high transmission capacity is likely ($p_H \geq K$), the operator can obtain W_1. He can for instance disclose no information ($\rho_{H1} = \rho_{L1}$). The message does not contain information, and the generator bases his information on his ex-ante belief. Ex-ante it would be optimal for him to behave. Other strategies, which give not too much information to the generator are possible as well.

If small transmission capacity is likely ($K > p_H$), the operator can only implement W_2. He uses the following strategy:[4]

$$\rho_{L1} = \frac{\Delta X}{\Delta Y} \frac{p_H}{p_L} \tag{7.7}$$

$$\rho_{H1} = 1 \tag{7.8}$$

If network capacity is high, the operator will always tell the truth $\rho_{H1} = 1$. If capacity is low, he will lie with probability ρ_{L1} and tell the truth with probability ρ_{L2}.

7.4 Optimal strategy: no commitment

Suppose now that the Operator cannot commit to a disclosure strategy in stage (-1). We then need to check whether the disclosure strategy of the network operator is incentive compatible in stage (1).

Clearly, the strategies described in 7.7 and 7.8 are no longer an equilibrium. If the network operator uses this strategy, the belief of the generator is

$$\mu(M_1) = K \tag{7.9}$$

$$\mu(M_2) = 0 \tag{7.10}$$

Given this believe, the network operator would send message M_1 in both states of nature ($\rho_{H1} = \rho_{L1} = 1$). Hence, 7.7 and 7.8 do not form an equilibrium.

It can be shown that the network operator is not able to reveal any information to the generator.

7.5 Conclusion

If the operator cannot commit to share information, he cannot credibly disclose information to the generator.

If the operator can commit, he should not give all information to the generator. Sharing information would increase misbehaving by the generator. More specifically, if low transmission capacity is unlikely, he should give no

[4] They are the highest ρ_{L1} and ρ_{H1} that satisfy $\mu(M_1) \geq K$ and $\mu(M_2) < K$, and thus maximize W_2.

information. If low transmission capacity is likely, he should give some but not all information.

Relation with the literature

The game in this paper is actually a signalling game (Spence, 1973) where the signals are costless. Therefore, the messages of the network operator are cheap talk. They will never be believed by the generator.[5] In the standard signalling game, messages (signals) are costly. As a signal can be cheaper to send in one state of the world than in another, the generator has reasons to believe the network operator.

The model in this paper is a principle-agent model. The principle (network operator) has more information than the agent (the generator). These types of models have been studied in general by Maskin and Tirole (1990, 1992).

[5] We have thus a pooling equilibrium.

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