The Scandinavian Electricity Power Market and Market Power

Haukur Eggertsson

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Preface

This thesis on the Scandinavian electricity power market and market power, was written as part of my studies for a Master degree at the Department of Informatics and Mathematical Modelling (IMM) in the Technical University of Denmark (DTU), under the supervision of professor Henrik Madsen.

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Haukur Eggertsson
haukureg@strik.is

Abstract

Recent high prices on the Scandinavian electric power market have led to public scrutiny of the market and have been the source of investigation of legal authorities.

Although the Nord Pool[1] spot market is considered to be one of the most successful electricity markets in the world, and one of few international electricity markets, the market is small in comparison to many other commodity markets, and is as such, together with the difficulty of storing electricity, less liquid and subject to more instability in prices and supply. In addition, due to limited transmission capacities between the areas that form the common markets, prices often vary between market areas. This can also give electricity generators a large market share in different areas, even though they only hold a modest market share on the total market.

This thesis is a study of the possible uses of market power on the Nord Pool spot market and how this kind of market behavior, especially with regard to the game theory and Nash equilibria, can be detected.

This is certainly not by any means an accusation against any member of the Nord Pool market, although the theoretical possibilities of some of them exercising market power, is discussed.

My findings are that searching for Nash equilibria is not the most effective way of market power detection, due to the many uncertainties involved and the lack of information market power users as well as market power detectors will face.

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[1] The Scandinavian power exchange

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Part I

Background

Chapter 1

Introduction

1.1 Introduction

The main motivation behind this thesis is based on the concern that market power is possibly being used on the Scandinavian electricity market, Nord Pool, i.e. on the spot market, and on how such a suspicion can be reinforced by analysis.

Eltra, the transmission system operator in western Denmark, see section 10.2.4, has worked with IMM (the Department of Informatics and Mathematical Modelling at the Technical University of Denmark (DTU)), on a number of different projects concerning electricity, such as wind power and the electricity market in general. Eltra has shown interest in the possible use of market power on the Nord Pool spot market, and has suggested studies on the matter with special reference to the game theory and Nash equilibria, at IMM. To follow up, Eltra has provided data and other useful information, on which this thesis has mainly been based on.

The recent high prices on the Scandinavian electric power market have been the source of speculations whether market power is being used and whether the deregulation of the Scandinavian electricity power market is justified.

Both Nord Pool and transmission system operators have an interest in reinforcing the credibility of the market and are consequently interested in detecting unusual market behavior.

The Nord Pool market area consists of Denmark, Norway, Sweden and Finland, each with different sources of energy, demand and production behavior. The limited transmission capacity of electricity between the markets creates an interesting situation where, under certain circumstances, producers, with a small market share on the overall market, will find themselves holding a large market share in their own market when congestion occurs. As large market share is one of the key factors for market power to be profitable, these temporary semimonopoly situations may offer some tempting opportunities for certain producers.

1.2 Overview

In Chapter 2, *The Scandinavian electricity market*, I describe the establishment of the common Scandinavian electricity market.

In Chapter 3, *Nord Pool*, I discuss and describe the functions of Nord Pool, especially its spot market and the geographical markets on which Nord Pool operates.

In Chapter 4, *Electricity*, I discuss the characteristics of electricity, its distinction from other commodities as regards storing and transmitting, and the different sources of electricity.

In Chapter 5, *Market power*, I define market power and the necessary information that must be available for its detection.

In Chapter 6, *Competition*, I discuss the different forms of competition, and their theoretical background.

In Chapter 7, *Game theory*, I introduce the element of the game theory I will use in this thesis as well as defining certain concepts.

In Chapter 8, *Data and Machines*, I discuss the data and the computers used for calculations in this thesis.

In Chapter 9, *Characteristics of the Scandinavian electricity market*, I discuss precisely that.

In Chapter 10, *Market power on Nord Pool's spot market*, I introduce the possible market power users, discuss different forms of market power and finally how market power may be detected.

In Chapter 11, *Price strategies*, I discuss how individual electricity producers should choose their price strategies in order to optimize their profit.

In Chapter 12, *Price calculation algorithms*, I discuss some various methods for calculating prices on the Nord Pool spot market.

In Chapter 13, *Search algorithms*, I introduce some methods for the search of Nash equilibria and Pareto optimal solutions for short and long periods of time. I will also compare the findings to the actual prices of time as well as discussing the value of the findings for the detection of market power.

In Chapter 14, *Conclusions*, I draw my final conclusions.

Chapter 2

The Scandinavian electricity market

2.1 Overview

The Scandinavian countries have traded electrical power for decades and thus have one of the world's most developed international power market. In the last decade, the trading system has changed dramatically, moving from the old model of cooperation among the leading vertically integrated utilities in each country, under the Nordel agreement, to competitive market rules. (Nord Pool).

The differences in the mixture of power generation largely explain the establishment of interconnections in Scandinavia. Norway relies entirely on hydropower, while Denmark generates most of its power in thermal plants, mainly from imported coal and, lately, increasingly from wind power. Power generation in Sweden is a mixture of about half hydro and half nuclear generation, and in Finland it is mixture of hydro (25 %), conventional thermal (45 %), and nuclear (30 %) plants. The differences in the power generation structure have made it economically attractive to trade power, allowing the countries to optimize production.

These countries also have strong cultural and economic ties, even though Norway is currently outside the European Union (EU). However, as a member of European Free Trade Association (EFTA), Norway is also a member of the European Economic Area (EEA), which in a way intergrades some of the EFTA countries, i.e. Norway, Iceland and Liechtenstein into the EU, applying large bits of EU legislation to the area with the aim to make trade between the EEA members as easy as between members of the EU.[1]

2.2 The old structure

Before the move to the international pool, the power sectors of Norway, Sweden and Finland all had an oligopoly structure, with dominant state owned enterprizes that also controlled the national grids, even though there were differences in structure, ownership, and regulation.

Norway's power sector was dominated by the government owned integrated utility Statkraft, which also operated the national grid. There were also many small local and regional utilities. Between fifty and sixty companies, many owned by local or regional authorities, were involved in the transmission of electricity at the regional level. The local and regional utilities had gained access to the national grid in 1969 and could buy and sell power through a spot market. Electricity was distributed locally by around 200 companies, many of which were owned by municipalities.

In Sweden, about half the generation was government owned through Vattenfall, which also operated the national grid and provided distribution services in parts of the country. About ten other integrated utilities of various sizes also used the national grid, but a relatively high network fee made it uneconomic for smaller utilities to use it. Like Norway, Sweden had a large number of distribution companies, many owned by municipalities.

In Finland the state owned Imatran Voima Oy (IVO) was the largest utility. IVO also operated the national grid. However, much of the power generation was owned by Finnish industries, which formed a transmission company, TVS, to interconnect their generation and supply areas.

In Denmark, for geographical reasons, the grid is divided into two main parts: Jutland and Funen (western Denmark) and the islands east of the Great Belt (eastern Denmark). In each of these two areas the generation and distribution utilities, mostly owned by municipalities, formed special purpose organizations to manage the extra high-voltage grids and the coordinated operation.

Trading of electricity between the countries was enabled through Nordel, an organization set up in the 1960s to promote cooperation among the largest electricity producers in each country. Nordel was based on the principle that each country would build enough generating capacity to be self-sufficient. Trading was meant to achieve optimal dispatch of a larger system, and investment in interconnection was generally based, not on net exports, but on expected savings from pooling available generating capacity. The countries exchanged information on their marginal cost of production. When there was a difference, trading took place at a price that was the average of the two marginal costs.

The cost-plus structure in the Nordic power sector led to over investment and poor return on equity. But because the system retained a degree of competition, there were no significant operating efficiency problems in the utilities.[1]

2.3 The shift to a market based structure

The shift to an international pool was triggered by power sector reforms in Norway starting in the early 1990s. Norway introduced competition in electricity supply in 1991 through reforms aimed at reducing regional differences in the cost of power, promoting operational efficiency in generation and distribution, and achieving more efficient development of the power sector. Statkraft's transmission activities were spun off to a new national grid company, Statnett SF. In addition, all transmission networks were opened to third-party access, and vertically integrated companies had to adopt separate accounting for generation, distribution, and supply activities.

In Sweden, reform was fuelled by discontent among the private power companies stemming from Vattenfall's control of the national grid, and dissatisfaction among the smaller power companies and among customers over their lack of access to the market for occasional power. The first major step, taken in 1991, was to corporatize Vattenfall's generation and distribution activities. However, Vattenfall remains government owned. The national grid was retained as a government owned institution, Svenska Kraftnät, which also serves as the system operator. The networks were gradually opened to new players, and a new electricity act allowing a competitive market finally took effect in January 1996.

Finland introduced a new energy legislation in 1995. IVO had already organized its grid activity into a separate company, IVS. But with the privately owned grid company TVS, Finland had two overlapping grid companies for several years. Since September 1997, Finland has had a single, merged grid company, Fingrid, which also acts as the system operator.

Reform moved more slowly in Denmark because of the power sector's different structure, with two unconnected groups owned by municipalities or cooperatives, each with a monopoly in its area. A new legislation was introduced in 1996, opening the grids to negotiated third-party access and allowing competition for large consumers, distributors and generators.[1]

2.4 The creation of a pool

Norway led the way in reform, by opening up a spot market in 1992. A similar power market in Sweden would have been problematic to manage, as Vattenfall and Sydkraft, the two largest generating companies, together control about 75 % of generating capacity. However, the Norwegian market also experienced problems. Because almost all the power in Norway is produced by hydroelectric plants, the spot market price was very volatile. A combined Norwegian-Swedish market would address the problems of both countries. A decision was therefore made to establish a joint electricity trading exchange in January 1996, the design being based on the Norwegian experience. The grid operators own the company, Nord Pool, that organizes the market. Finland joined the power exchange in June 1998. western and eastern Denmark joined in July 1999 and October 2000 respectively.[1]

2.5 Ownership and structure

Setting up the pool did not require privatizing government owned companies. A mixture of companies continues to operate in the Nordic power sectors, from large government owned utilities to privately and municipally owned companies of various sizes, running generation, regional networks and distribution systems, and supplying power to consumers. But ownership of the international interconnections that existed in the Nordel area, when the sectors were restructured in Finland, Norway and Sweden, has been transferred to the grid company in each country. This has opened trading to all the players in the wholesale markets; generators, distributors, and large consumers.

Competitive pressures in the electricity market have resulted in several changes in ownership and structure in the sector, including some cross-ownerships between countries and the entry of some foreign power companies. In addition to the traditional power companies, other players can trade on the market, including brokers, oil companies, foreign power companies and power trading companies representing consumer groups.[1]

2.6 Competition

Strict regulation of the electrical network service ensures that third-party access works. However, it is generally assumed that the market is able to take care of itself under the supervision of national competition authorities.

With increasing privatization of the electricity generation, the forming of the Scandinavian electricity market was also intended to reduce the risk of monopolistic behavior and the use of market power, while the benefits of free enterprize would be enjoyed.

However, around Easter 2002 prices rose and the difference between electricity sold and electricity offered on the market became so great that an investigation was launched, reaching all the Scandinavian electricity producers. Therefore, the use of market power is considered to be a real possibility.[2]

Chapter 3

Nord Pool

3.1 The functions of Nord Pool

Nord Pool operates three markets, each with a different purpose. In this thesis, however, the main focus will be on the spot market, Elspot. The other two are the Financial market and Elbas.

3.1.1 Elspot

The spot market for electrical power, organized by Nord Pool, trades in hourly contracts for the following day. It is open to all parties that have signed the necessary agreements with Nord Pool. Bids are submitted each morning, and supply and demand curves are then constructed to provide the price (the system price) and the traded quantity for each hour during the next day. The price of the power to balance the system is also determined through bidding. Elkraft, Eltra, Statnett, Svenska Kraftnät, and Fingrid are each responsible for balancing the system in their areas. When differences in prices prevail between areas, these companies tariff the electricity until balance is obtained with full use of the international transmission lines. These tariffs can be vast if the price gap between countries is great.

Example 3.1 *If the market price in Norway is x and the market price in Sweden is y, $y > x$ and the power which can be delivered from Norway to*

Sweden is z*, the transmission system operators in Norway and Sweden will split the profit of* $(y - x) \times z$

The Elspot market is a day-ahead physical-delivery power market and the deadline for submitting bids for all delivery hours of the the following day is **12 am (noon)**. The products traded on the Elspot Market are bids of a one-hour duration, block bids and flexible hourly bids.

Contracts on the Elspot market are one hour physical power (delivery to or take-off from the grid) obligations; minimum contract size is 0,1 MWh/h.

Hourly Bid is a sequence of price/volume pairs for each specified hour. Volumes are stated in MWh. In bidding, purchases are designated as positive numbers and sales as negative numbers.

Block Bid is an aggregated bid for several consecutive hours with a fixed bidding price and volume. The block bid price is compared with the average hourly price within the block period. A block bid must be accepted in its entirety and if it is accepted the contract covers all hours and the volume specified in the bid.

Flexible Hourly Bid is a sales bid for a single hour with a fixed price and volume. The hour is not specified, but instead the bid will be accepted in the hour with the highest price, given that the price is higher than the limit set in the bid.

The trade on the spot market amounted to 124 TWh in 2002 or 32% of the total electricity consumption in Scandinavia for that year, and rose from 29% from 2001.[4]

Further information about Elspot areas and bidding information can be found in appendix A.

3.1.2 Financial market

In addition to the spot market, Nord Pool offers futures contracts, which are traded as weekly contracts four to seven weeks ahead, as blocks of four weeks up to 52 weeks ahead, or as seasons up to three years ahead. The futures are purely financial contracts used for price hedging. The bulk of the volume traded is in standardized financial contracts, often referred to as over-the-counter (OTC) contracts. The liquidity of the OTC market is quite high, particularly for the nearest season. Contracts can be resold, or a position netted out by making an opposite contract.

In addition to the spot and futures markets there is direct trading between parties in bilateral forwards. These bilateral contracts normally involve physical deliveries and are often tailor-made to particular requirements. Despite the diversity in trading instruments, most of the trading between players still takes place under bilateral contracts for physical delivery which were signed before the reform.[5]

3.1.3 Elbas

The Elbas Market is a physical market for power trading in hourly contracts for delivery on the same or next day. It enables trading around the clock every day of the year, covering individual hours up to one hour before delivery. One function is to be the adjustment market to the Elspot Market. The participants are mainly power producers, distributors, and industries and brokers in Finland and Sweden.[6]

3.2 The geographical markets

The Nord Pool market is composed of five market areas with several limitations of electricity transmission between them. These areas are: Denmark, which is divided into two areas by the Great Belt, Norway, Sweden and Finland.

3.2.1 Eastern Denmark

Eastern Denmark (DKE) consists of all the Danish islands east of the Great Belt, with the exception of Bornholm. It has connections to Sweden and Germany, but not to western Denmark. Eastern Denmark depends heavily on coal and wind power for electricity generation.

3.2.2 Western Denmark

Western Denmark (DKW) consists of Jutland, Funen and other smaller islands west of the Great Belt. Western Denmark has connections to Norway, Sweden and Germany. It depends primarily on coal and wind power for electricity generation.[7]

3.2.3 Norway

Norway (NOR) has connections to western Denmark, Sweden and a small one to Finland. Norway has also connections to Russia. For electricity generation, Norway depends mostly on hydropower. Due to internal transmission limitations of the Norwegian power grid system, tariffs are used on the congested points. Therefore there can be different prices in different areas of Norway.[7]

3.2.4 Sweden

Sweden (SWE) has connections to all the other markets of Nord Pool as well as to Poland. The Swedish electricity market depends mainly on hydropower, nuclear power and other thermal power as coal and gas plants. When congestion occurs in the Swedish local grid transmission system, Svenska Kraftnät buys more expensive power from areas where the market price causes power shortage; i.e. buy enough of power from inside the area to satisfy demand, at price above the market price. The extra cost caused by this intervention is covered by fixed charges on the users of the transmission system.[7]

3.2.5 Finland

Finland (FIN) has connections to Norway and Sweden on the Nord Pool as well as to Russia. Finland depends mostly on coal, nuclear and hydropower for electricity generation.[7]

3.2.6 Northern Germany

Although northern Germany (NGE) is not part of the Scandinavian Power market, it is currently the only area which is expected to have similar prices as in Scandinavia. Unlike Russia and Poland which also have connections to Finland and Sweden respectively, the import from these countries is usually fixed as the maximum import possible due to international transmission restrictions. However, the similarities between the Scandinavian and German prices make the German market more interactive. In this thesis, the German market is therefore sometimes considered a special market area, although strictly speaking it is not. The data used for most calculations assume power plants and production in northern Germany which may interact with the other markets. northern Germany has connections to both Danish markets as well as to Sweden. The northern Germany's power supply comes mainly from nuclear, coal and wind sources.[7]

Chapter 4

Electricity

4.1 Characteristics of electricity

Since its first practical application in the 19th Century, electricity has become one of the most essential elements of modern society. Without it most services would cease to operate and, in the western world, electricity has been taken for granted for almost a century.

The characteristics of electricity vary from many other products. As with most commodities, prices will, in the long term, reflect the production cost of the last unit sold. If not producers will either drop out of the market or new ones enter. However, electricity differs from most other commodities in three ways.

1. Lack of storage ability. There is no economically viable storage of electricity and though it can be stored in all kinds of batteries, e.g. hydrogen cells, storing large quantities is both expensive and inefficient. Therefore, the same volume of electricity used must be produced each time, and while the consumption of electricity varies during the day and between seasons, so must the production. Hence, there is never any stock in reserve, nor can low consumption periods be used to prepare for high peak consumption periods. This makes the price of power vary considerably during the hours of the day, and between seasons, as temperature is one of the key consumption variables.

2. Transmission. Transporting electricity is subject to other law than most commodities. If the necessary grid lines are available, electricity can be transmitted in a very short time over long distances, even though this may affect its quality. However, these grid lines have a limited transmission capacity and are often not available. Thus, electricity needs its own kind of infrastructure for transmission as opposed to most other commodities.
3. Inelastic demand. Studies indicate that electricity demand is usually relatively inelastic and will respond only slowly to consistent price pressure. Most customers still pay fixed prices based on rate schedules set by regulators. Short time demand curves are almost vertical.

4.2 Sources of power

The main sources of power for electricity generation in Scandinavia are:

- Hydropower
- Nuclear power
- Coal and oil
- Gas
- Wind power

In the following section the characteristics of these different sources will be discussed briefly.

4.2.1 Hydropower

Hydropower is the main source of energy in Norway and, to a lesser extent, in Sweden and Finland. There are two kinds of hydropower plants, dammed sites and free-flowing sites. Dams are often expensive to build, but cheap to maintain and operate. Although fuel cost is essentially zero while the water lasts, and there is no emission of waste into the environment, the dams themselves, often with a huge man-made reservoir lake and thus sinking of land, have been the source of increased environmental concern. The potential of harnessing more hydropower in Scandinavia is considered almost exhausted.

Free-flow hydropower plants are not very flexible, even though they tend to produce more during the day than the night, but then again more during the summer than the winter when the need for energy is greater. Plants using water reservoirs are far more flexible and can store water during low demand periods, but there is of course a limit to how much they can produce during peak demand. There is also the uncertainty of how much water will flow into the reservoir during coming seasons, which means that the operators of such dams will want to save the reservoir for times with high power prices and thus limit the availability of cheap power. Therefore, it is quite difficult to estimate the "production cost" of reservoir hydropower plants. It can therefore be in the interest of consumers that hydropower plants do not offer their prices at too low levels as it may cause the reservoirs to empty before spring and thus generate very high prices, from which the hydropower owners will not benefit, having spent all their water earlier. As free-flow hydropower plants can be treated much like windmills, only more predictably, the power will be sold at any price, i.e. minimum price or zero at the auction.[8]

4.2.2 Nuclear power

The only nuclear power plants in Scandinavia are to be found in Sweden and Finland. Although fuel cost for nuclear plants is lower than for coal or gas plants, maintenance and security cost is higher, and building these plants is more expensive and more time consuming. Nuclear power plants emit virtually no airborne pollutants, and overall far less waste material than fossil fuel based power plants. However, this relatively small amount of waste, which is in the form of highly radioactive spent fuel and needs to be handled with great care and forethought due to the long half-lives of the waste, has been of environmental concern. There is also the security risk, often connected with accidents at Three Mile Island and Chernobyl, but also in case of terrorism and war, which theoretically could end in a disaster. Nuclear power plants are also quite inflexible in production and it takes long time to either increase or decrease the production, i.e. they do not handle peaks very well.[9]

4.2.3 Coal and oil

The burning of coal and oil to generate energy and hot water, is the main power source in Denmark and Finland, and to a lesser extent in Sweden and Germany. The benefits of coal and oil power plants are that they are rather cheap to build and operate, but the fuel cost is higher than for nuclear plants although lower than for gas plants. They can also, as a side product, be used to heat water for commercial use such as domestic heating, especially during the winter. This means that the operation of coal plants is more profitable during the winter when demand for both electricity and hot water is normally higher. As coal plants are often required to produce hot water, power will be sold at any price. However, the emission problem with fossil fuel goes beyond greenhouse gases and includes acid gases (sulfur dioxide and nitrogen oxides, which is also a greenhouse gas), particulates, heavy metals (notably mercury, but also including radioactive materials) and solid waste such as ash. Due to the above and international environmental agreements such as the Kyoto Protocol, the use of coal plants has increasingly been the source of environmental concern.

Coal plants are inflexible; it takes a long time to increase or decrease the production and especially to start production after a shutdown. As a result, some old and inefficient coal plants are only used during the winter or dire electricity shortages.[10]

4.2.4 Gas

The burning of natural gas, is increasing in all over the world, although its market share is rather low in Scandinavia. Building cost is relatively low, maintenance is cheaper than for coal plants, but the fuel is more expensive. Environmentally speaking, natural gas is a relatively clean-burning fuel, although it does produce greenhouse gases. Gas plants are also much more flexible than coal plants and can therefore easily adapt to peak demand.[11]

4.2.5 Wind power

Denmark is one of the leading countries in the world in the harnessing of wind power. Windmills do not emit any kind of particulates, maintenance cost is low, and there is no fuel cost. However, the power from windmills is highly unpredictable as can been seen in figure 4.1, and can vary greatly even during a single day as seen in figure 4.2. There is also the visual “pollution” of windmills, even though they can rather easily be removed unlike dams. Offerings of power from windmills are usually submitted to the spot market at very low prices, as variable production cost is very low and power not sold is lost at no value. However, as more expensive power usually decides the market price, wind power can be profitable when winds are favorable.[9]

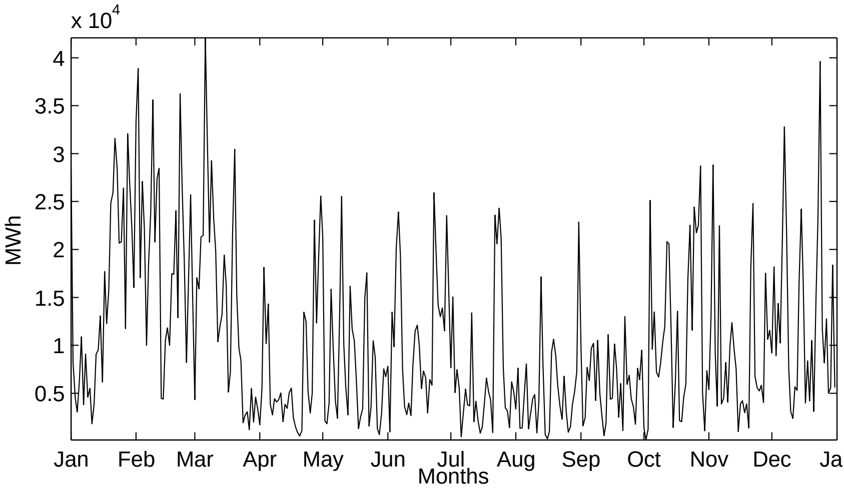

Figure 4.1: Daily wind power in western Denmark in 2002

4.2.6 Other sources

Other sources of energy are dismissive. They include e.g. sun energy, tide harnessing and a few more. These are usually only used privately by the producers and therefore do not affect the market to any extent.

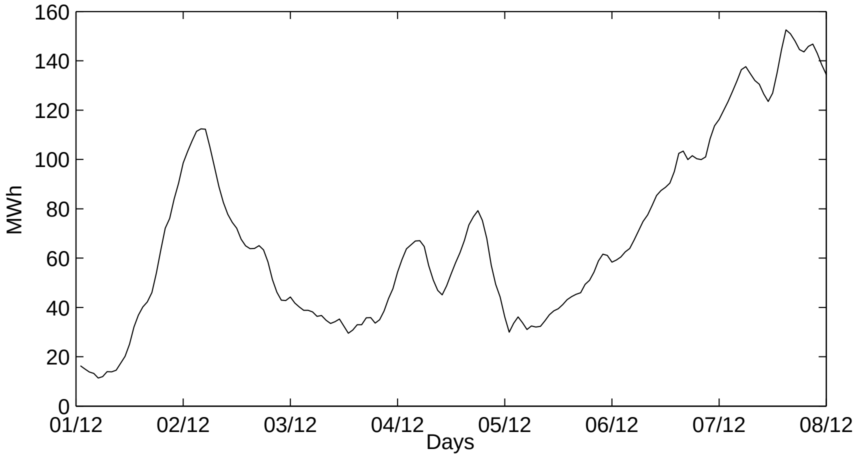

Figure 4.2: Wind power per hour from December 1st to 7th 2002 in western Denmark

Part II

Theory

Chapter 5

Market power

5.1 Competition, monopoly and oligopoly

The classic model of perfect competition assumes that competitive markets consist of numerous suppliers who compete at setting the price of their output at marginal cost. Each supplier is too small to affect the market price by on his own. If a supplier attempts to increase prices above the competitive level (i.e. above the marginal cost), he will lose all his customers and either be forced to lower prices or go out of business. Similarly, if the supplier reduces output, this will not affect the market price because the supplier's output is too small to significantly reduce the market output. In other theoretical models, suppliers may set prices above marginal cost, yet still not attain supracompetitive prices due to high fixed costs. This is possible as, even though fixed cost may be sunken, new suppliers will not enter the market unless the fixed cost can be covered, which will then function as a market barrier for new suppliers.

In the classic model of monopoly, the monopolist can reduce output and increase prices, but at the cost of sales. Similarly, as large suppliers acquire greater control over production in a specific market, they increase their ability to affect prices in the market.[13]

However, market power entails a social cost, as the producer surplus will increase less than the decrease in consumer surplus. Thus, use of market

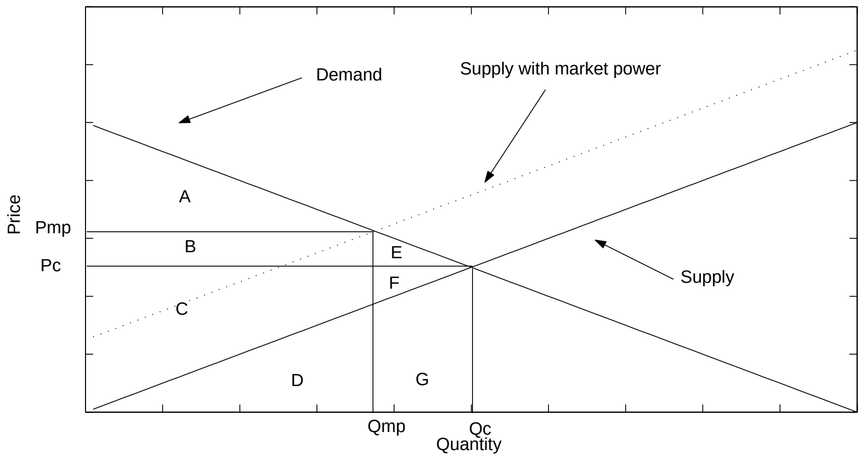

Figure 5.1: Use of market power

power is contrary to the idea behind deregulation of the electricity market where competition was intended to lower cost and increase overall wealth (surplus) in society.

Economists use the terms ‘producer surplus’ and ‘consumer surplus’ for the combined profit either group will make when price has been settled. Then the consumers, who were ready to pay more than the actual price for the product, have made their profit as well as the producers who were ready to sell for less than the actual price. The total social surplus is the combined consumer and producer surplus which is always maximized when the marginal cost (MC) of the last unit sold is the same as the price. Or when the supply function is the same as the MC function.

To explain figure 5.1, P_c and Q_c respectively are the prices and quantity sold during perfect competition. Area $A+B+E$ is consumer surplus. Area $C+F+D+G$ is producers income and $D+G$ is producers cost. Thus $C+F$ is producer surplus and total social surplus is $A+B+E+C+F$. However, by using market power the producers are able to shift the supply curve upward and new equilibrium would be gained at price P_{mp} and quantity Q_{mp}. The consumer surplus is now A and the producer surplus is $B+C$. As B is larger than F, the producers are profiting more. The society surplus

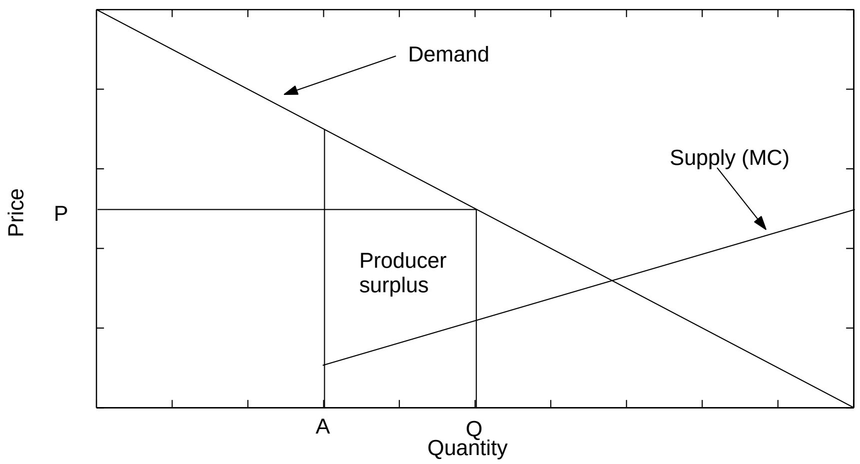

Figure 5.2: Assuming bids from competitors

is now made up of $A + B + C$ and has shrunken by $E + F$.

The principal problem on the electricity market arises during periods of peak demand. During such periods, there may be only a small number of electricity generators with discretionary capacity. The opportunity for various forms of price boosting then develops. Clearly, the desire to maximize profits encourages electricity generators to constrain their competitive inclinations. If the suppliers can collude and behave as monopolists, they can increase the price and their collective profits. However, antitrust laws make explicit collusion very risky.

One theory of quasi-collusive behavior is the Cournot theory. The essence of the Cournot theory is that a supplier, bidding into a market, in which there are only a few sellers, e.g. during a peak demand period, will assume that the quantity bid by the other electricity generators will be the same as it was in the last similar period and, as a consequence, the supplier can assume that the remainder of the market demand curve is his to exploit. Therefore, the supplier will bid like a monopolist for that segment of the demand curve. If all suppliers behave in a similar way, there will be an equilibrium price, which is higher than the competitive price.[14]

If competitor A is expected to bid a quantity of 'A' in figure 5.2 in the next period, then competitor B can assume that the demand curve to the right of 'A' belongs to him. His profit maximizing position, where the area 'Producer surplus' is largest, is a bid of quantity Q which will generate a price P. It can be shown that if A responds by taking B's bid quantity as a signal of what he will bid in the next period and behaves as B behaved, the two competitors will converge to an equilibria price that is higher than the competitive price and lower than the monopoly price. Similarly, the market quantity will be lower than the competitive quantity and higher than the monopoly quantity. At this convergent price, the two parties will satisfy each other's expectations. This is called oligopoly.

Further and more theoretical and mathematical explanations of different forms of competition are given in chapter 6.

5.2 Detection of market power

How can we know whether market power is being exercised or whether fair competition is maximizing the total profit in society? There are a few things that must be known:

Production cost is essential information, in order to be able to know whether market power is being used. If we do not know the cost, we do not know the profit. If the market price is the same as the production cost of the last unit produced, there is no market power.

Demand Without it there would be no sales. Without information on the demand, producers cannot know which strategy to pursue.

Alliances or degree of cooperation between producers, often with vertical or horizontal ownerships, must be known to understand the overall benefit of the actions of a single producer to an Alliance..

When those information are available, they can be used to find:

Nash equilibria are when every producer is trying to maximize his own profit. The existence of a Nash equilibrium, unless Pareto optimal, also indicates that there is no active cooperation between players. Unless the Nash equilibrium is where price is at production cost, there is market power. See chapter 7.1 for further explanations of Nash equilibria and Pareto optimality.

Pareto optimality is not only a clear sign of the use of market power by individual players, but unless it is also a Nash equilibrium, a sign of active or inactive cooperation between players. If some of the players are cooperating, then, if any player can lower his price and thus increase his profit, this is not a Nash equilibrium. This suggests cooperation as the higher price may be part of agreement between some of the players. See table 7.1. However, if all cooperating producers are defined as a single producer, the Pareto optimal solution becomes a new Nash equilibrium.

Chapter 6

Competition

6.1 Perfect competition

In perfect competition, the price, y, and quantity, x, of goods are when supply and demand is the same. Supply, $S(x)$, is the unit cost of producing the last of x goods. Demand, $D(x)$, is the unit price consumers are willing to pay for quantity x of the goods. There is, however, a difference to these curves, as when price y and quantity x have been decided, all goods are sold at the same price but not produced at the same cost. Therefore the price,

$$y = D(x) \tag{6.1}$$

for produced quantity x, and the total income for sold quantity x is therefore

$$x \times y = x \times D(x) \tag{6.2}$$

but the total cost of producing quantity x is

$$\int_0^x S(x)\,\mathrm{d}x \tag{6.3}$$

6.2 Monopoly

The definition of monopoly is that there is either one player on the market or no competition from other players. In a monopoly situation, there is not necessarily the same price and quantity of the goods as under perfect competition, as the monopolist is likely, unless under threat of competition or regulations, to want to maximize his profit, $f(x)$. Hence quantity x is not where

$$S(x) = D(x) \tag{6.4}$$

but when his profit is maximized.

$$Max\left(f\left(x\right) = \left(x \times D(x) - \int_0^x S(x)\,\mathrm{d}x\right)\right) \tag{6.5}$$

Which is when ...

$$\left(\frac{\mathrm{d}f(x)}{\mathrm{d}x}\right) = x \times D'(x) + D(x) - S(x) = 0 \tag{6.6}$$

Quantity is therefore decided when the extra income of producing and selling one more unit equals the loss of revenue for the lower price of all other goods sold by that competitor or when

$$y + \Delta y - p_i \times x \times \Delta y = S_i(p_i \times x + \Delta x) \tag{6.7}$$

where $S_i(x)$ and p_i are respectively the supply function and market share of competitor i, which in case of monopoly is the single supplier with 100% market share. And when $p_i \rightarrow 0$, the negative part of equation 6.7 $\rightarrow 0$ and the remaining parts equal equation 6.4.

6.3 Oligopoly

The definition of oligopoly is that there are only a few relatively large players on a market. They will usually not find it profitable to compete more than necessary.

When p_i in equation 6.7 is neither close to zero nor close to one, we have oligopoly. When oligopolists are few, the price and quantity of goods which maximize the total profit of all oligopolists, are the same as in monopoly. Therefore, when there is a full cooperation between the oligopolists we have, according to the definition, a monopoly.

Situations can arise, during fierce competition between oligopolists, when a producer chooses to sell his product at a lower price than equation 6.8

would indicate, as he may fear that other players will dump the price if he does not.

Equation 6.7 equals:

$$MR = MC \tag{6.8}$$

where MR is the marginal revenue of selling an extra unit and MC is the marginal cost of producing it.[26]

Chapter 7

Game theory

7.1 Definition

The game theory is a branch of mathematics and logic which deals with the analysis of games (i.e. situations involving parties with conflicting interests). In addition to the mathematical elegance and complete ‘solution’, which is possible for simple games, the principles of the game theory can also be applied to complex games such as cards and chess, as well as real problems as diverse as economics, property division, politics and warfare.

Some useful game theory definitions: [25]

Cournot game is when all players secretly and separately decide how much to produce.

Nash equilibria are when no player gains from deviating from his current strategy given, the strategy of other players. This way, no player will immediately profit by choosing another strategy and thus there is an equilibrium. Strategies chosen this way may be either pure or mixed.

Pure strategy is when a single strategy is always selected. Player with single strategy becomes very predictable.

Mixed strategy is when one strategy is randomly selected from a pool of strategies with certain a probability. Players with mixed strategies are less predictable than those who follow pure strategy.

Pareto optimality is when there is no other solution where any player is better off and no player is worse off. Nash equilibria can be, but are not necessarily, Pareto optimal.

Dominant strategy dominates other strategies if the choosing player is better off choosing it, regardless of other players' strategies.

Information is crucial when games are played. Do all players know each other's actions? Do players know each other's costs and benefits of each of their strategies? Do players even know who the other players are? Knowing the enemy can help in games as in war. If everybody does not know everything about the other players, we talk about incomplete information.

Repeated game is a game which is repeated either for a certain period or indefinitely. In a repeated game, reputation becomes important and in a game which for example is repeated every day or every hour, with repeated behavior or threats, a player can influence the play of others. Therefore, if there is some kind of an informal agreement on not to rock the boat, the reaction of other players to someone lowering the prices might be sanctions and price wars which would last until it is certain that the deviating player has lost more with his deviation than the profit he gained with it. The other players should then return to the prior strategy if the deviating player is willing to do so.

Cooperative games are when players may freely engage in any kind of agreements in order to increase their profit. In a non-cooperative game, players either not able or not allowed to engage in such an agreement. The cooperation between competitors is often forbidden by the competition legislation of countries and cooperation on pricing on the Nord Pool market is strictly forbidden.

7.2 Games and market behavior

Tables are often used to explain simple examples of the game theory. In table 7.1 we have a Cournot game with two players where each player has two strategies, producing either little or Plenty. The first player chooses from the strategies on the left side of the table, and the second player chooses from the strategies at the top of the table. The letters in the boxes indicate the profit both players will attain when both have chosen a strategy. The first number, or letter in case of algebra, is the first player's profit and the second number is that players profit. Let $A > B > C > D$ and we have the famous ‘prisoner’s dilemma’.

	Little	Plenty
Little	B, B	D, A
Plenty	A, D	C, C

Table 7.1: Cournot game with two players

Here the dominant strategy for both players is to produce Plenty (P), even though both would profit more by cooperating and producing little (L). Both players producing P is therefore a Nash equilibrium, as neither player will benefit from choosing L, given the other player is playing P, but not Pareto optimal as both players producing L will give the same or a better profit to each player than the PP solution. LL is thus Pareto optimal but not a Nash equilibrium.

In an iterative repeated non-cooperating game, where both players expect the other to produce as Plenty as they did the last time, maximization of the profit for each player will converge to the equilibrium in equation 6.8 which is a Nash equilibrium but not Pareto optimal, assuming both $D(x)$ and $S(x)$ are continuous. However, it is possible that players will offer prices as low as production cost, fearing that the other will otherwise do so. The Nash equilibrium in equation 6.8 will probably be reached before that. See table 7.2 and let $A > B > C > D$.

	Little	Plenty
Little	A, A	D, B
Plenty	B, D	C, C

Table 7.2: Down to production cost

Here we have two Nash equilibria, LL and PP, but no dominant strategy. LL is also Pareto optimal but PP is not. It can also be seen that if the currently chosen strategies are at either LP or PL, the player playing P gains from deviating to L and thus, unless the players begin in PP, they should end in LL.

On most markets, a simplistic explanation of the game would be as given in table 7.3.

	Monopoly	Oligopoly	Competition
Monopoly	B, B	D, A	G, D
Oligopoly	A, D	C, C	F, D
Competition	D, G	D, F	E, E

Table 7.3: Different stages of cooperation

The game in table 7.3 is still a two player game put together from tables 7.1, as the upper left part, and 7.2, as the lower right part. Let $A > B > C > D > E > F > G$. The strategy 'Monopoly' (M), represents the quantity sold during monopoly; 'Oligopoly' (O) and 'Competition' (C) represent what would be expected to be sold during oligopoly and perfect competition respectively. Quantity $C > O > M$. There are two Nash equilibria, OO, which represents both PP from table 7.1 and LL from table 7.2, and cc, as the PP equilibrium in table 7.2. However, MM is Pareto optimal to both solutions. This means that players have to, either actively or inactively, cooperate in order to keep the MM solution, as the short term benefit for both players would be to lower prices, even though the logical response would cause both players to be worse off in the end. The CC solution is a trap which players can end in after a price war and when there is no trust between players. Although this table is presented as a discreet strategy, this is surely not the case. However, there are three fixed points.

1. The MM solution is as during a monopoly, and so is the profit. The total profit of all players is maximized. No player would profit more from less volume and thus a higher price. However, as this point is not a Nash equilibrium, players will be tempted to deviate from this solution in the hope that other players will not react. However, for every extra quantity until o, the consequences will be the same: more profit if no response from the other player, less profit if there is a response. If both players start to underbid each other they will eventually end at OO.
2. OO represents the natural competitive oligopoly solution from equation 6.8. From this point, players will only lose by lowering prices, unless others are already underbidding them.
3. CC represents where the price equals the production cost of the last unit produced. Players can only lose by lowering prices to below that price.

This clearly demonstrates that it is not always wise for a player to deviate from a strategy, even though more profit can be gained temporarily. In a repeated game, this may lead to either active or inactive cooperation where lack of competition causes prices to be higher than they otherwise would.

7.3 Mixed strategy

An example of when a mixed strategy is the best choice, can be found in table 7.4. Here, the correct strategy, and in fact a Nash equilibrium, of both players would be to randomly select either L or P, each with a 50% probability each. If one of the players only reacted to the other player's strategy, with his next choice, he would become predictable. The other player would always know which strategy to expect and would be able to respond accordingly and thus always gain A while the predictable player would always have -A.

	Little	Plenty
Little	A, -A	-A, A
Plenty	-A, A	A, -A

Table 7.4: No pure strategy

7.4 Reputation and threats

One aspect of repeated games has to do with reputation. If a player has the reputation of reacting in a certain way, this may influence the strategy of others. This may, in the end, mean that the player with the reputation to barely ever having to use the strategy on which he has built his reputation. If a player always reacts to competition with fierce resistance, this may cause other players not to try further probes into his realm. And even if the fierce competition is more costly than a more conciliatory approach, other players may choose not to try to underbid the player as they will expect to lose by doing so. However, if the player has a “soft” reputation, other players will constantly harass him as they will not fear retaliation. This is demonstrated in table 7.5.

Defender	Contender	
	Does not compete	Competes
Soft	A, 0	0, A
Hard	A, 0	-B, -A

Table 7.5: Hard or soft?

The defender is better off by always taking hard stand against competition when

$$\frac{A}{A+B} \geq P_{competition} \tag{7.1}$$

$P_{competition}$ is the probability of another player entering into competition. It can be assumed that other players will always enter into competition if the defender has the reputation of being soft.

In games, threats can play a significant role. Threats are often closely connected with reputation and, like reputation, are used to force other players to behave in a certain way. For threats to be credible, the player who makes the threats must be able to harm (economically speaking, hopefully) other players, at not too high a price for himself. If the threats are costly for the threatening player, he may be considered bluffing and if the player fails to live up to his threats, his reputation may be ruined. Threats are a form of forced cooperation and are usually an illegal behavior on consumer markets, and in breach of competition and antitrust legislations. Threats can be either direct, as in communications, or indirect by making examples of other unfortunate players, and thus by reputation.[25]

Part III

Study

Chapter 8

Data and machines

8.1 The data from Eltra

8.1.1 Supply and demand

Eltra maintains a database over most of the electricity power plants in Scandinavia. Eltra has estimated output capacity and the cost structure of individual types of power plants. Eltra has also made estimates of the demand curves in each of the six markets. Northern Germany, which, as explained in section 3.2.6, interacts more closely to the Nord Pool area than any other neighbor, is therefore included.

The data does not take into account the ownership of some producers in other power plants, unless they are the sole owners.

This estimation can of course never be a precise estimation of the true operating cost of each and every power plant in the area, but should give a close enough picture to at least understand the mechanism and the weight of individual power plants and their type, and to understand the possibilities at hand. Neither can the demand curve be precisely estimated, especially outside the most common price range. However, this data gives an excellent platform for developing tools of detection, as they should give a fair estimate of the market structure.

The data is an output from a program named MARS, developed by Eltra, which is a market model for the simulation of prices, production, demand

and exchange on the power market. Ownership of production capacity is a basic model parameter on the company level. Wind power and free flowing water is modelled as a supply with low marginal cost, and the hydropower bids are taken from the EMPS model[1].

Much has been written about the pricing of electricity from hydropower and its relation to water reservoir level, long time weather forecast etc. In this thesis I will not add anything to that discussion but use the data from the EMPS model via Eltra, without reservations.

The data comes as hourly bids from a number of plants, characterized by ownership, type and location on a market. The bids are either given in steps, where all units will be sold at same price or with a linear increment where the next unit will only be sold for more than the last unit. Indeed they do fulfill the requirements for bids as given in appendix A.

The data mainly used in this thesis is from February 2003 and is the week from Monday the 10th to Sunday the 16th.

However, as results may vary considerably, even though there was only a small error in price or volume of a single bid, results must be taken with reservations. Only the current price and volume traded and offered is available from Nord Pool and the true operating cost of plants is only known by their owners.

When viewing the data, I noticed, due to the lack of elasticity of the estimated demand, that the most favorable strategy for the producers as a whole is to offer a very small quantity of power at very high prices. One would assume that such kind of behavior would be unacceptable to the governments of the region, but this makes optimization a little difficult as one has to estimate the highest acceptable price without risking an interference from governmental institutions. The data also indicates that the buyers are ready to pay more, in total, for little power than for a lot. This seems to be a paradox but does not interfere with the calculations based on the data. The demand is simulated with the equation:

$$p = k \times q^{1/\beta} \tag{8.1}$$

where p and q are price and quantity respectively and β and k are constants. This means that the total income from sales increases with sales when

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[1] Integrated model for market based economic optimization of hydro-thermal production systems (main focus being on hydropower). Sintef, Trondheim [32]

$$\frac{1+\beta}{\beta} > 0 \tag{8.2}$$

or when $\beta \geq 0$ or $\beta < -1$.

This data is confidential and is not presented in this thesis, although calculations based on it are.

8.1.2 Other data from Eltra

Other information from Eltra derives from an interview with Berith Bitsch Kristoffersen and Bjarne Donslund, Market Power Model Seminar held at Eltra in April 2003, and from Eltra's web site,[2] where some useful information and data can be found.

8.2 Nord Pool

Data was also received from Nord Pool via their web site[3] and through correspondence with Hilde Rosenblad, Market & Development at Nord Pool Spot.

8.3 Sunfire

The computer most frequently used for calculations and data processing is Sunfire 3800 with eight 1200 MHz UltraSPARC CPUs (central processing unit) and 16 GB RAM (random access memory).[4]

My personal laptop, MITAC 8575 with Pentium IV two GHz CPU and 256 MB RAM, was also used, performing almost as well as the Sunfire in matlab.

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[2] http://www.eltra.dk

[3] http://www.nordpool.no

[4] Further information can be found at http://se.sunsolve.sun.com/handbook_pub/-Systems/SunFire3800/spec.html

Chapter 9

Characteristics of the Scandinavian electricity market

9.1 Overview

The electricity market in Scandinavia is a repeated game with incomplete information, a bidding game where the lower bids are cleared out with the price of the highest accepted bid. There is no information available, other than the price and volume traded on each market, from Nord Pool. The number, price and volume of all bids, supply and demand, are therefore only speculations. Therefore, it is quite difficult for others than Nord Pool themselves to estimate whether and when unusual market activity may be taking place. We will, however, sometimes assume that all this information is available to us so that we may anticipate players' strategies.

Consumption of electricity depends on the hour of the day and the day of the week, see figure 9.1 which shows a week of consumption in Sweden. Consumption is less during weekends than working days and less during the night than the day, as less power intensive activity is taking place at that time. Consumption is also greater during the winter as electricity is used for domestic heating, especially in Norway, where only a small quantity of

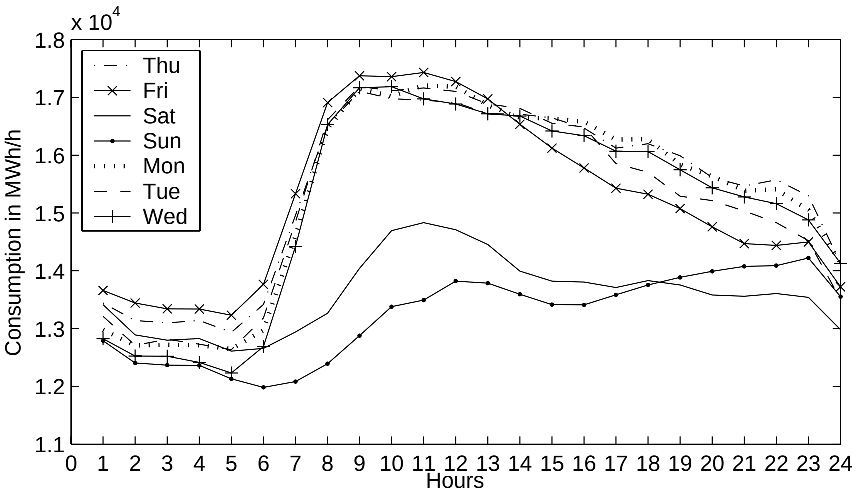

Figure 9.1: Hourly consumption in Sweden May 15^{th} to May 21^{st} 2003

the electricity is generated from the burning of coal and other fossil fuel. And due to the geographical position of Scandinavia in the northern reaches of the inhabited world, air conditioning during the summer, which is quite power intensive, is not as common as in more southern lying countries.

Because of this and according to the data, the demand seems to be rather stable and predictable on a daily basis, and the main deviations seem to depend on the hour of the day, holidays and, to a lesser extent, temperature. I also found it surprising how little difference there is in consumption over 24 hours. The supply, however, varies more. The reason for this is for example unpredictability of the availability of cheap wind power in the short term, and water reserve in the longer term. The price of energy from thermal power plants, like coal plants, varies demand for the side product, heated water, is abundant in winter. Therefore, the volume and price of the supply can vary considerably.

Because of this seasonal and regional difference in supply and demand, Denmark for example, is usually a net exporter of energy during the winter but net importer during the summer.

Ultimately, there is only one offer that matters: the one that will be clear

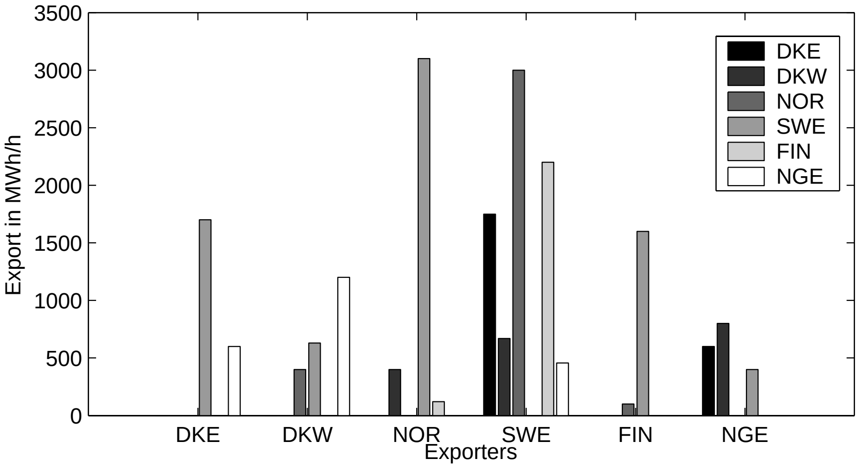

Figure 9.2: Maximum possible export from each area

	DKE	DKW	NOR	SWE	FIN	NGE
DKE				1700		600
DKW			400	630		1200
NOR		400		3100	120	
SWE	1750	670	3000		2200	456
FIN			100	1600		
NGE	600	800		400		

Table 9.1: Maximum export from row to column in MWh/h

out the others. We will refer to this offer as the highest accepted bid. If demand and supply are known, each player, unless he has a small market share, can influence the price on the market either by increasing an already accepted offer of his to above the highest accepted bid, or by lowering an existing bid to below the highest accepted bid. Any other price changes that do not put the bid in question on the other side of the highest accepted bid, will neither influence the price nor the volume traded on the market.

9.2 Competition and cooperation

The market can be divided into five areas (six including northern Germany) with limited transmission capacity between them. See figure 9.2, where the columns indicate maximum export from each of the markets, and table 9.1. Let us imagine that all electricity generators in each of the areas are a single player and the market is thus a game of six players. Each player then operates in a protected environment, where only limited competition can be employed due to the transmission limitations of power between the areas. This does of course not hinder all competition, but strengthens the market power each player can wield in his own area. This seriously weakens the threats that players can make to other players on other markets. Threats are a way of getting others to cooperate or behave in a more convenient manner. The transmission limitations decrease the likelihood of cooperation between players, as it is less enforceable and there are more limits to what can be gained from international cooperation.

Example 9.1 *If player A wants to punish player B in another market, he can only do so if the price on his market is either above or the same as the opponent's home market price. If the market price of A is higher than the market price of B, A must reduce his market price until it is as low as B's. When this has been accomplished, there is a common price area and both players operate as if they were on the same market. From this point, A can economically punish B by reducing the price on the common market, but only as long as the market remains common, as once A has reduced his price to a certain level, the price on market A becomes lower than on market B, and will no longer influence B's profit.*

Therefore, interaction between players is limited to the transmission capacities between them and when there are no longer any such capacities available, players will no longer be able to influence the prices on other markets. The player with more sales will usually lose more from price reductions.

9.3 Demand

Although in general all suppliers will benefit from raising their prices, given strict limitations on deviating from the current supply curve, suppliers with a small enough market share may benefit from lowering their lowest bid, be it not accepted or only partially accepted, in order to underbid a competitor and thus replace the competitor's sales with his own.

There can, however, never be an optimal strategy in the common interests of all suppliers to lower the prices in order to expand the market, given the steep form of the demand curve.[1] As can be seen in figure 9.3 which shows the Swedish market, in the early morning of Monday, February 10, 2003, selling more will always reduce the total income from sales. The curves show the total income from the Swedish market when different volumes of electricity are sold at the market by Swedish producers. The upper curve is when there is no cheap foreign import and the lower curve is when foreign income pours into the Swedish market causing lower prices. However, in both cases, the income will always diminish when more is sold and at the same time, cost will increase, so the total profit will drop even faster than is demonstrated in the figure. The equilibria sales are between 20 and 25 GWh and yield far less profit to power generators than if no competition was taking place in Sweden.

Figure 9.4 shows the demand curve of the Finnish market. If the price is at 'Price 1', the total income from sales on the market will be the size of boxes A + B. However, if the price is reduced to 'Price 2', the the total income becomes A + C. Under all circumstances box C seems to be smaller than box B, and thus the total income drops with lower prices. In addition, the total cost is higher at 'Price 2' than 'Price 1', ensuring the folly of low prices for the producers.

Lowering prices to just under the highest accepted bid of a competitor can be an optimal strategy when there are strict limitations on how the supply curve may be manipulated, as increasing the prices sufficiently to profit more, may not be "legal". Consequently the limitations to the behavior of players contribute to the complexity of the calculations, instead of simplifying them.

In a normal market there can be two motives for lowering prices and one for increasing prices. Motives for lowering prices are: to gain market share and to increase the size of the market. Of these, only the former seems to be valid on the electricity market, due to inelastic demand. And the motive for increasing the prices can only be to increase profit, despite a lower market

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[1] With the possible exception of eastern Denmark in extreme cases, as import can cover larger part of consumption there than on other markets

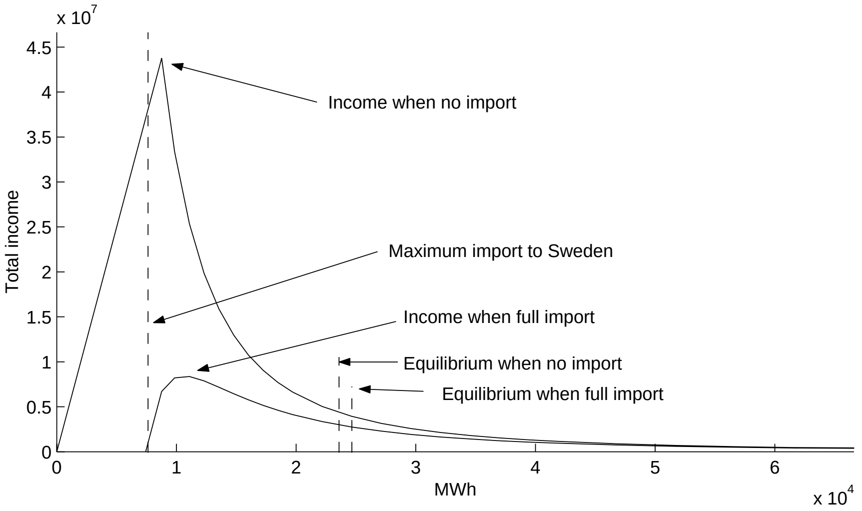

Figure 9.3: Total hourly income from sales in Sweden

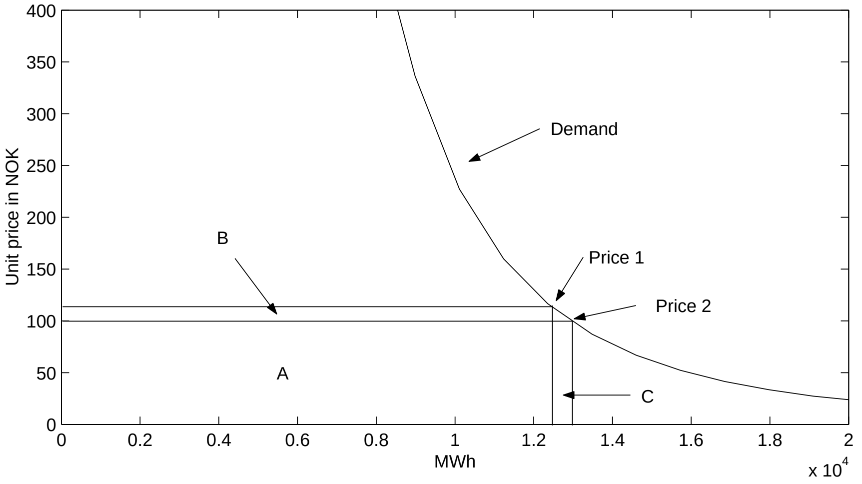

Figure 9.4: Demand in Finland

share and a smaller market. Having thus limited the factors that influence the optimal strategy of each player, the problem should simpler.

However, as all electricity producers in certain areas (hopefully) do not act in unison to provide themselves with a monopolistic profit, but are likely to compete, the strategy of raising prices or withholding production for players, especially those with small market share, is not necessarily profitable. This is why there is usually some competition, even on markets with few competitors, although the competition may sometimes seem limited. Monopoly is usually not a Nash equilibrium unless with only one player.

Chapter 10

Market power on Nord Pool's spot market

10.1 Who could be using market power?

Market power has its price. When someone exercises market power, he does so in order to increase prices, but at the cost of sales. Thus, the use of market power involves sacrifices. In order for these sacrifices to be worthwhile the effort and if profit is to be increased, enough market share, or merely sales, must remain to overcome the sales loss.

$$\Delta y \times (x + \Delta x) + y \times \Delta x + \int_{x}^{x+\Delta x} S(x)\, dx \geq 0 \tag{10.1}$$

In the above formula, x and y respectively are the actual volume sold and the price, before the use of market power and $S(x)$ is the supply or production cost function. Δx and Δy are the difference in sales and price when market power is used. Δx would be negative as less is sold, but Δy positive as the price will rise. The first component of the equation is the increased revenue due to higher prices, the second component is lost revenue due to less sales, and the third component, the integral, is the saving in production cost due to less sales. If the sum of these items is greater than zero, the use of market power will yield an increased profit for the player in question. In figure 9.4 the income part is explained and equation 10.1 may be rewritten as follows:

$$\text{area } B - \text{area } C + \text{saving of production cost} \geq 0 \qquad (10.2)$$

As y, Δy and Δx will be the same for all players, the size of x will determine for which players will be rewarded by the use of market power.

To be able to use market power, the players must be able to influence prices. In order to do so, Δx must be large enough. Sometimes the highest accepted bid is large and only partially accepted. Thus, Δx must be larger than the unaccepted part of the highest accepted bid as well as less than the previous sales x.

The conclusion is that only big producers are likely to benefit from using market power.

10.2 Big producers

In the Scandinavian power market area, there are several large producers with production which is often limited to only one of the markets. They tend to have a large market share on their home market even though their total market share in the combined market area may be modest.

In my calculations I will often consider the profit and opportunities of E2, Elsam, Statkraft, Vattenfall, Sydkraft, Fortum and E.On and refer to them as the 7 power players. In addition Elkraft and Eltra are large sellers of electricity, but being system operators in their own areas, they are not considered to exercise market power.

The largest power producers will now be briefly discussed.

10.2.1 ENERGI E2

ENERGI E2 is a leading Danish production and energy trading company. They own and operate seven large power stations and eleven small ones as well as CHP (Central heating plants) in eastern Denmark and hold shares in a number of hydropower plants in Sweden and Norway. In addition to this, E2 owns wind turbines in Sweden, Greece and Spain.

The company was founded in June 2000 as the result of a merger between SK Power Company A/S, Københavns Energi Produktion A/S and EK Energi Power Company A/S.

The aggregate electricity production at E2's generating facilities in Scandinavia was 12.5 TWh in 2002. Wind power generated 0.4 TWh. Production at the hydropower stations in Sweden amounted to 0.8 TWh. The major part of the remaining 11.3 TWh was produced at CHP plants in eastern Denmark.

E2 has been increasing their share in wind power recently. Neither the new windmills nor E2's shares in the Norwegian and Swedish hydropower plants are represented in the data and are therefore omitted in the calculations.[16]

10.2.2 Elkraft

Elkraft is the transmission system operator in eastern Denmark and owns most of the high-voltage lines in the area. The company was established when the Danish electricity market was liberalized.

Although Elkraft does not produce electricity itself, Elkraft administers the distribution of the environmentally friendly electricity that all electricity consumers in Denmark must use. Elkraft is a non-profit company and is as such not supposed to exercise market power.[17]

10.2.3 Elsam

Elsam is the largest producer of electricity and district heating in Denmark. Elsam operates 6 central and 23 local CHPs as well as 486 windmills on Jutland and Funen.[18]

10.2.4 Eltra

Eltra is the transmission system operator in Jutland and on Funen, and is responsible for the overall security of supply in that area. Eltra bears the responsibility for developing environmentally friendly electricity generation and incorporating it into the system. Eltra owns, develops and operates the 400 kV network as well as the connections to neighboring countries.

Besides this, Eltra manages the 150 kV network, forming part of the overall Jutland-Funen transmission network.

In cooperation with other electricity supply undertakings and system operators in Denmark and abroad, Eltra is to contribute to developing and operating the electricity supply industry efficiently, while taking due consideration of security of supply, the national economy and the environment.

The new Danish Electricity Supply Act gives power stations, distribution undertakings and industrial customers (of a certain size) the right to freely enter into agreements on purchase and sale of electricity in Denmark and abroad. It is an important task for Eltra to open the new electricity market and make it work. This requires that the transmission network should be expanded in accordance with market demand, that there should be open, strong connections with the neighboring countries, that there should be access to an efficient power exchange, mirroring the market value of electricity at any time, and that all players should gain network access on uniform, nondiscriminatory terms.[3]

Eltra is a member of the Nord Pool spot market as it acts as an agent for some windmill owners in western Denmark.

10.2.5 Statkraft

Statkraft is Norway's largest producer of hydroelectric power. Annual production capacity exceeds 42 TWh, about 1/3 of the country's hydroelectric power production. The company has around 2,500 employees, and is firmly involved in developing power production based on renewable sources. Statkraft is state owned.

Statkraft holds a number of shares in the power industry in and outside Scandinavia. The most significant is Statkraft's 44% ownership of shares in the Swedish Sydkraft.

Statkraft is also engaged in power trading all over northern Europe.[19]

10.2.6 Vattenfall

Vattenfall is the state owned electricity producer in Sweden. It operates hydro, nuclear and thermal plants in Sweden, Finland and Germany. Prior to deregulation, Vattenfall operated the Swedish national grid.

Vattenfall has acted as a developer, investor and long-term partner in power projects located mainly in South East Asia and Latin America. [20]

10.2.7 Sydkraft

The Sydkraft Group consists of 60 operating subsidiaries. Approximately 5,300 employees handle electricity sales, electricity distribution, electricity production, natural gas, LPG, heat, cooling, water and sewage systems and energy, material recovery from waste, energy trading and communication solutions. These companies, together with a number of Group management functions, form a complete energy group.

Amongst other things, Sydkraft operates nuclear plants, hydro plants and CHPs. Most of them are situated in Sweden.

E.On in Germany owns 56% of Sydkraft against Statkraft's 44% share. In my calculations I will not take these ownerships into account.[21]

10.2.8 Fortum

Fortum is the second largest electricity producer in Scandinavia as well as being a leading energy company in other parts of the Baltic Rim. Fortum's activities cover the generation, distribution and sale of electricity and heat, the production, refining and marketing of oil, the operation and maintenance of power plants as well as energy-related services. The main products are electricity, heat and steam as well as traffic fuels and heating oils.

Fortum owns wholly or partly over 500 power plants in central Sweden, Greater Stockholm and in various parts of Finland. 60% of its power generation is renewable and over 80% carbon dioxide free. Fortum uses hydro, wind and nuclear power, coal, natural gas, peat, biomass and oil as energy sources.[22]

10.2.9 E.On

E.On is a German energy group which operates mainly in Germany. E.On is Europe's largest provider of energy services. E.On owns 56% of the Swedish Sydkraft.[23]

10.3 Winners and losers

Having identified the most probable users of market power, knowing which ones are there to gain and which ones are there to lose, may be important.

Those who might gain from the use of market power are:

1. The users of market power, otherwise they would not be using it. They will benefit from higher prices despite less sales.
2. Other producers. They will gain all the benefits from higher prices, without having to pay the cost involved with less sales. Peer pressure might help.
3. Grid line operators may gain from increased price differences between markets.

There are also a few on the losing side.

1. Sellers of electricity to end users, as they will either have to bear the higher cost or face less sales.
2. The public, which will have to pay higher bills.
3. The business will also have to pay more and that means less business.
4. The state. Less business means less taxes, and an unhappy public leads to fewer votes.
5. Nord Pool. Less credibility will affect their status. Nord Pool will not want its market to be considered the breeding place of monopolistic profit at the cost of the common good.

As a result, market power users may face formidable opponents.

10.4 The rules of the game

These are the ethical guidelines signed by all players of the Nord Pool spot market:[24]

1. All transactions made in Nord Pool's markets shall be performed with a genuine and generally acceptable business purpose.
2. No fictive transactions and mock agreements shall be carried out, and Participants and Clearing Customers must never give false or misleading expressions of their intentions with trades or bids and offers in the markets.

3. No bids or offers or trades shall be presented to the market with the purpose of misleading other Participants and Clearing Customers. Sudden changes in market behaviour that is not motivated by serious commercial or technical circumstances must not occur.
4. Any Participant or Clearing Customer that is a leading player in respect to the relevant supply or demand for electricity or electricity derivatives must assure that they do not in any inconsiderate way affect the price development in the relevant markets.
5. No misleading information must be given that can contribute to make a false and incorrect or misleading picture of the market situation.

These could be summarized into one commandment: Thou shall not exercise market power!

If we assume that everybody is follows these guidelines, we have nothing to worry about. On the other hand, it is human to err.

10.5 As time goes by

Market power can be used either to exploit a short term position or to maximize the expected long time profit. As there are often short term variations in prices, it could be very profitable to react immediately to opportunities as they arise. However, due to the restrictions imposed on players, as outlined in section 10.4, this can often be impossible as "serious commercial or technical circumstances" may not always occur when convenient, e.g. when windfall is expected during peak consumption hours, there is a failure in a large power plant etc., or when someone has recently started underbidding. Thus, players may rather want to focus on expected long term forecasts of the market and choose strategy, although inflexible, which will maximize their profit given their limited scope of operations.

10.6 How can market power be exercised?

The ultimate purpose of market power is to make more profit through higher prices, despite less sales. But there are a few paths to this goal. On the Scandinavian electricity market, the following are the most obvious:

- Raising prices

- Withholding production
- Wrong predictions
- Blocking grid lines
- Cooperation
- Leaving the spot market

Each of these elements will be discussed further in the following sections.

10.6.1 Raising prices

The most straight forward use of market power is simply to raise prices. However, due to the restrictions on market behavior, it is difficult to exploit at least the short term use of price raising. However, for long term opportunities, justification will be found for raising prices when the price of fuel goes up, unfortunate exchange rates develop, wages increase etc.; all of which is sometimes forgotten when circumstances become more favorable again. Then there is the question of the pricing of hydroelectricity. This makes changing prices confined mainly to long term use of market power.

When a player increases the price of his production, part of the supply function will rise and this may cause the order of offers to change. The system price will always increase equal or less to the player's increase. The reasons for this are:

- Demand is flexible. When prices rise, less will be sold.
- To influence prices, the producer must have offered such a high price to his accepted bids that after the rise, some of his offers will be higher than the former system price.
- The offers which rise above the old market price may be replaced with formerly unaccepted bids from other players, which now become lower than the player's bids.
- If the highest accepted bid is not wholly accepted, raising prices above the highest bid may thus not increase prices, as the bids, that rose above the highest accepted bid will be replaced with the unaccepted part of that bid.

Example 10.1 *If the demand is entirely inflexible and a player owns all bids on the market that are 5% above or below the system price, a 5% increase in the price would cause the system price to increase by 5% as well.*

Price strategies will be discussed further in chapter 11.

To demonstrate the possibilities of increasing profit, tests were run on the effect of the 7 power players' profit when they change the markup on their home market from 0% to 10%.[1] The data is from Eltra and is for peak consumption from 11 am to 12 pm on Tuesday, February 11, 2003. When no player is exercising market power, the market may be divided into two price areas: on the one hand western Denmark and northern Germany with price around NOK 155 per MWh and on the other hand the other markets with prices around NOK 207.

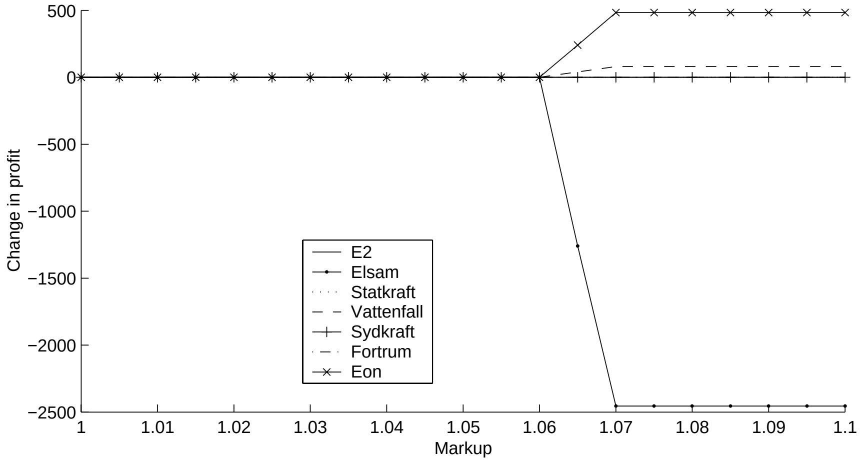

Figure 10.1: Tuesday: Changes in Elsam's profit with different markups

Neither E2 nor Statkraft succeeded in changing the prices on their market as they were not able to, raise any of their bids above the highest accepted bid, given the limited markup allowed, and are thus not demonstrated. Elsam and Fortum, figures 10.1 and 10.6, could not influence prices to any extent, but lost sales to others, and thus did not profit from their adventure. Sydkraft, figures 10.4 and 10.5, succeeded in changing the market price, but the all the benefit went to other players. However, Vattenfall and E.On were successful in increasing their (and other players') profit. See figures 10.2, 10.3, 10.7 and 10.8.

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[1] Eltra has suggested maximum markup being between 5% and 10%

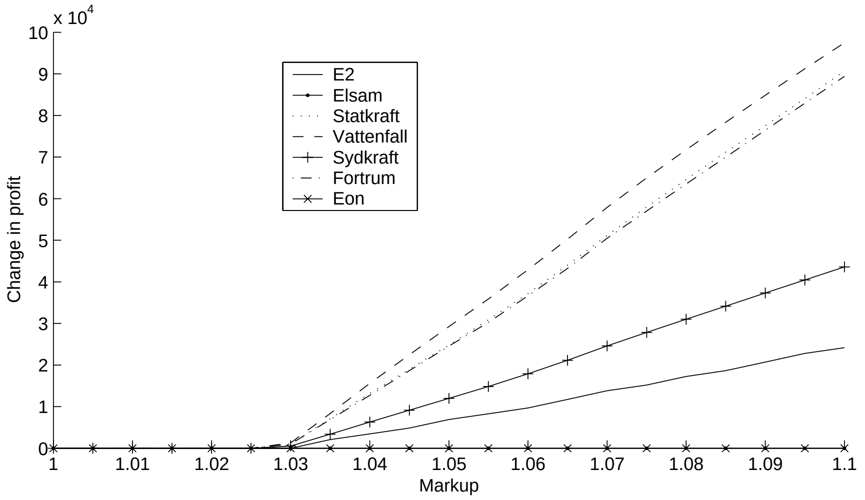

Figure 10.2: Tuesday: Changes in Vattenfall's profit with different markups

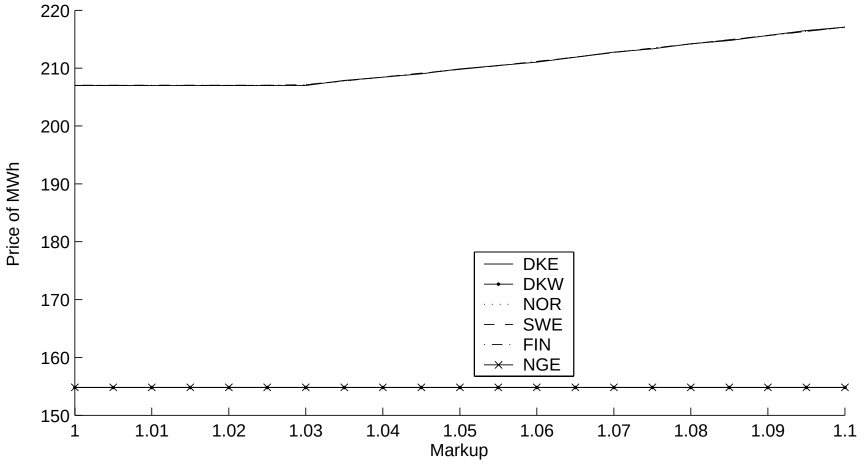

Figure 10.3: Tuesday: Prices when Vattenfall changes its markup

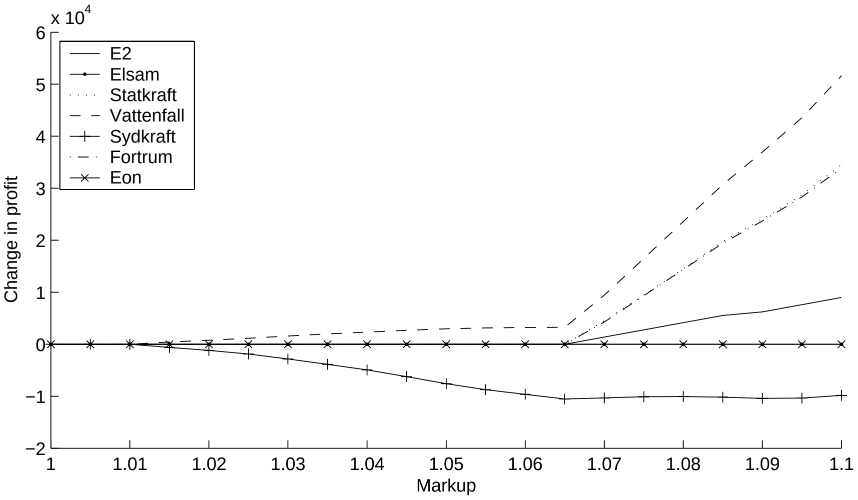

Figure 10.4: Tuesday: Changes in Sydkraft's profit with different markups

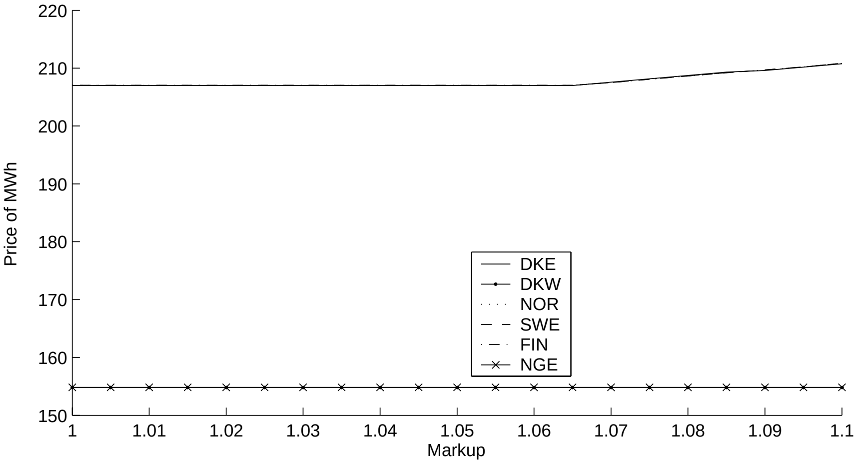

Figure 10.5: Tuesday: Prices when Sydkraft changes its markup

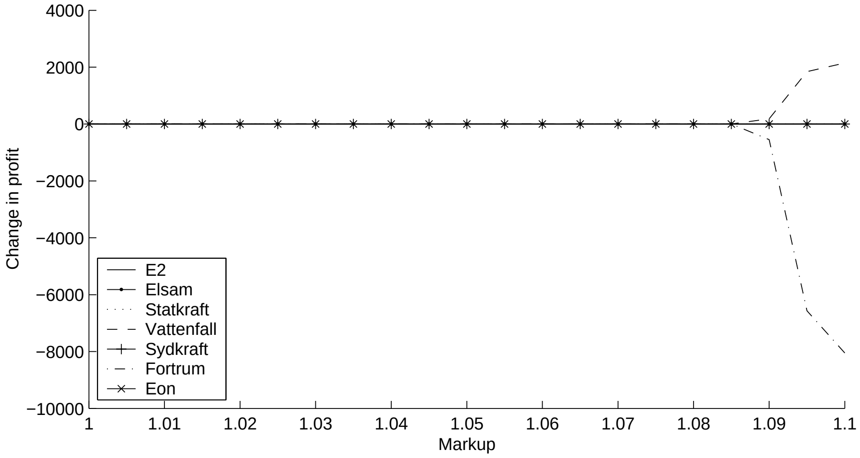

Figure 10.6: Tuesday: Changes in Fortum's profit with different markups

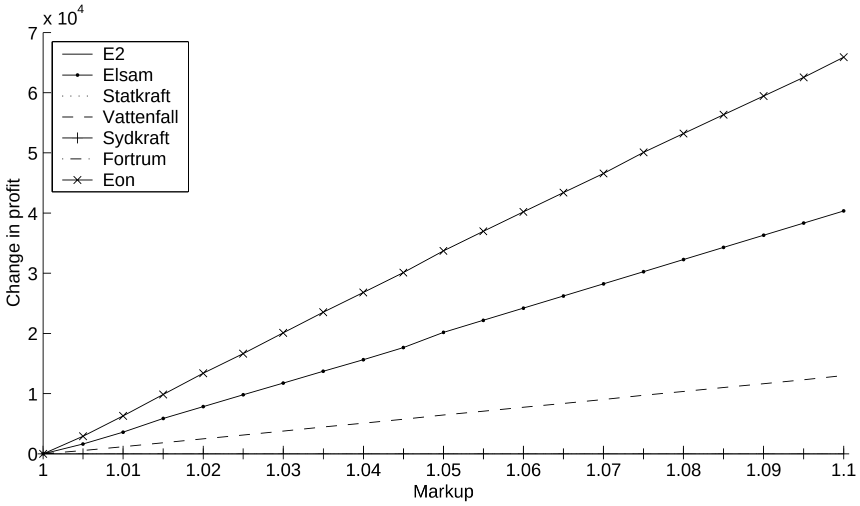

Figure 10.7: Tuesday: Changes in E.On's profit with different markups

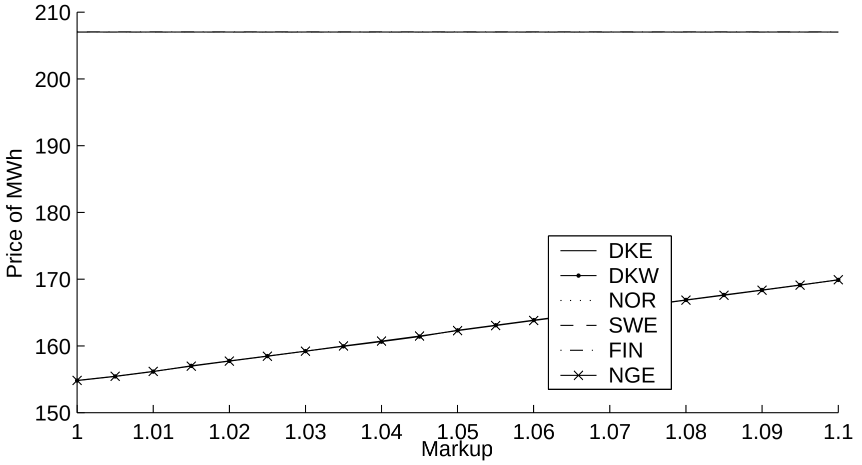

Figure 10.8: Tuesday: Prices when E.On changes its markup

According to this data, by increasing their markup by ca. 10% and therewith the system price in the area by ca. 5%, Vattenfall could increase their profit by ca. NOK 9,500 per hour, which would on a yearly basis sum up to NOK 83,220,000.

However, just 33 hours earlier, in the early morning of Monday, February 10, 2003, we have a different situation. Here there are three price areas with western Denmark at ca. NOK 132, eastern Denmark and Germany at NOK 154 and the rest at NOK 192 per MWh.

All players can, at this time, benefit from exercising market power, but some only modestly and with only a small markup, while others can cash in an extra handsome profit with a substantial markup. The Danes do well during the night: E2, figures 10.9 and 10.10, after they succeed in breaking away from the Germans and forming its own price area, and Elsam, figures 10.11 and 10.12, increases profit gradually with increased prices. In the north, prices change less, although Statkraft, with maximum markup in the end, succeeds in leaving the Finns behind, figure 10.14. However, Statkraft, Vattenfall, Sydkraft and Fortum, figures 10.13 to 10.17, only seem to benefit from modest markup as the rest of the profit goes to the competitors. E.On only manages to increase prices insignificantly, and is thus not demonstrated.

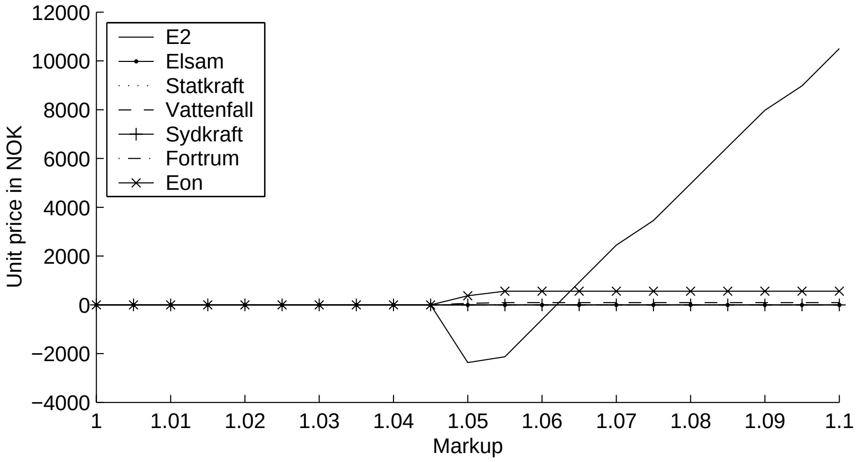

Figure 10.9: Monday: Changes in E2's profit with different markups

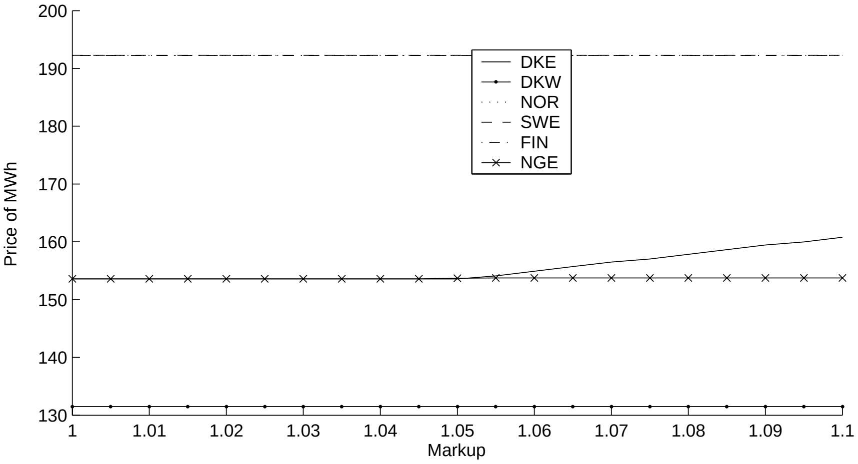

Figure 10.10: Monday: Prices when E2 changes its markup

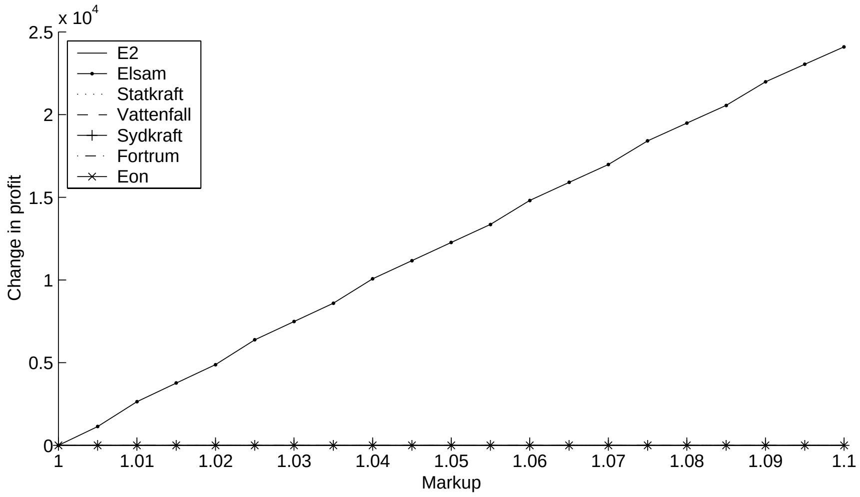

Figure 10.11: Monday: Changes in Elsam's profit with different markups

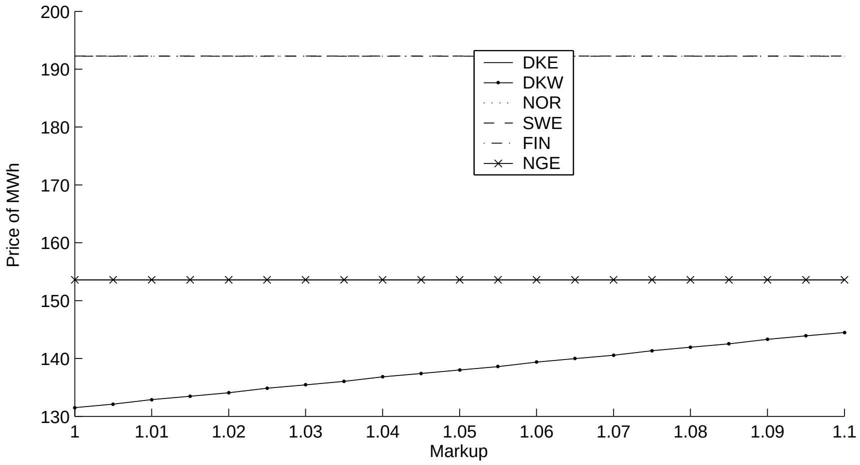

Figure 10.12: Monday: Prices when Elsam changes its markup

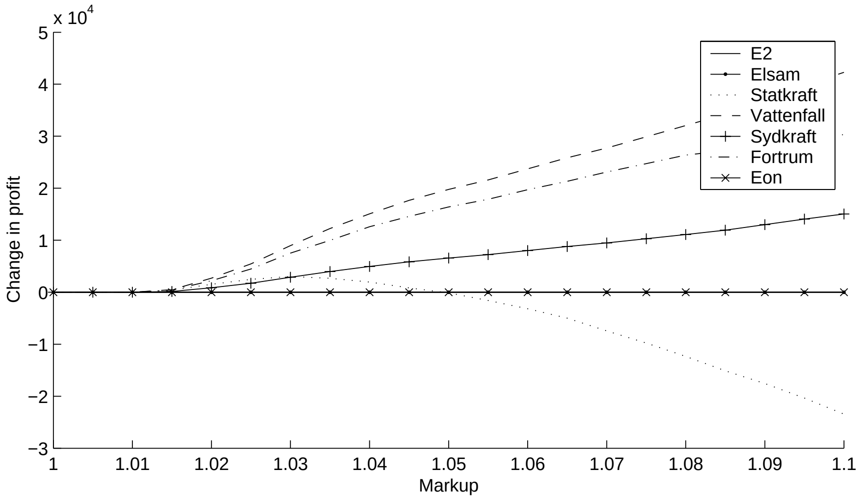

Figure 10.13: Monday: Changes in Statkraft's profit with different markups

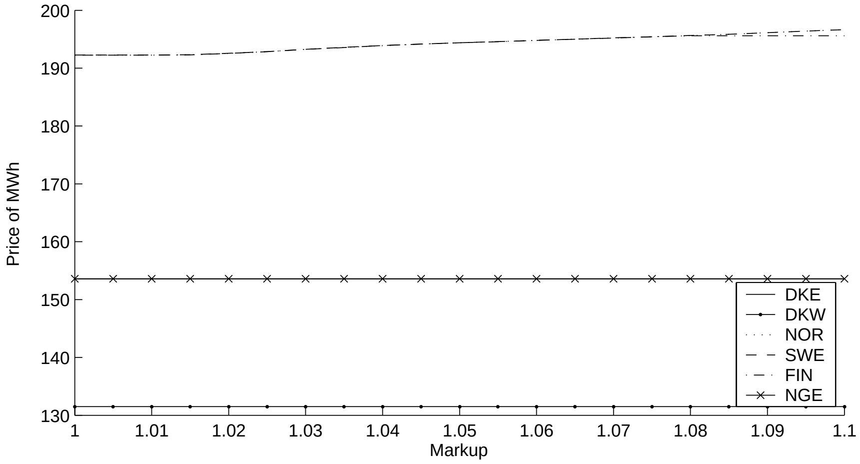

Figure 10.14: Monday: Prices when Statkraft changes its markup

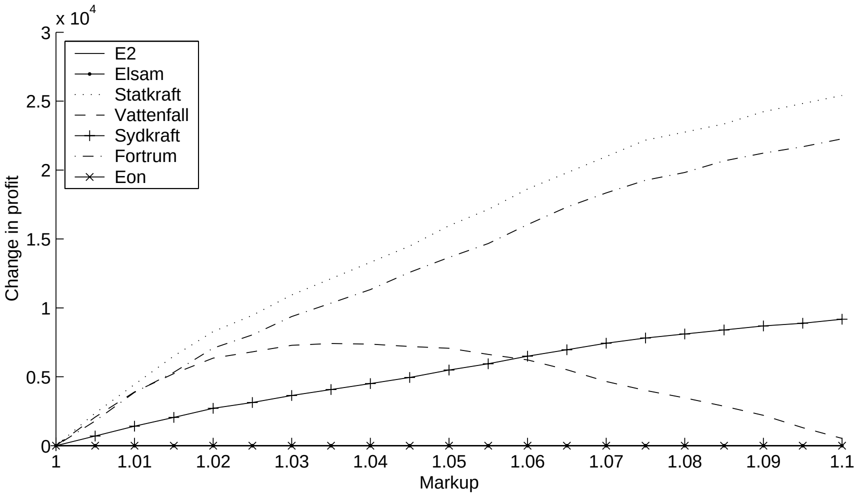

Figure 10.15: Monday: Changes in Vattenfall's profit with different markups

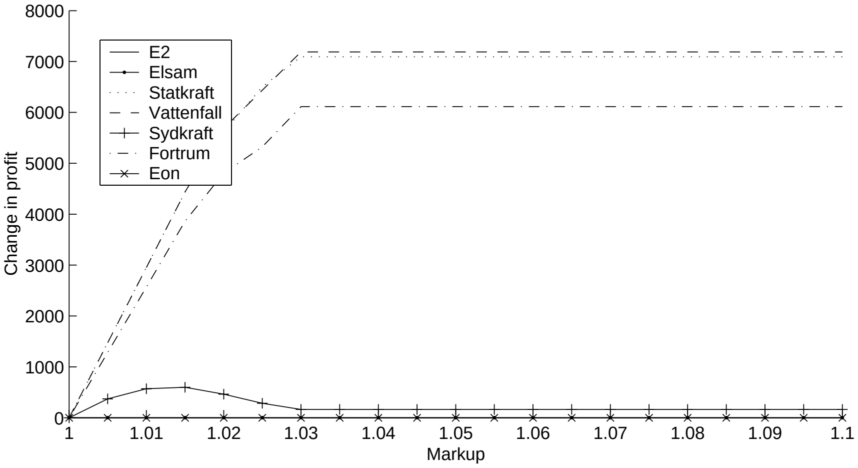

Figure 10.16: Monday: Changes in Sydkraft's profit with different markups

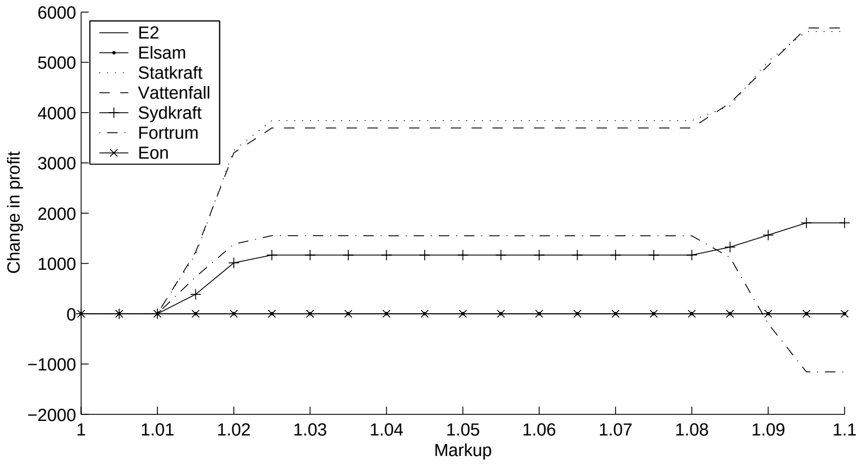

Figure 10.17: Monday: Changes in Fortum's profit with different markups

One can see how different markups will maximize profit at each time, which may complicate the price strategy of players as a price strategy cannot be easily altered. It is also worth emphasizing in these examples that when a player changes his markup, new markups may be optimal for other players.

10.6.2 Withholding production

The second most common form of market power is withholding production. Production can be withheld in several ways. The following may be the most obvious:

Maintenance of powerplants Outage, during necessary or unnecessary maintenance, can be profitable.

Outages and errors Sometimes powerplants simply fail to function. It can be very human to err.

Closing down Permanent closing of old and unprofitable (indeed) power plants.

Lack of investment Not building new plants, although they would be more cost efficient than the old ones. If it can be profitable to close down efficient power plants for maintenance, building new ones, would not be wise.

Cautious estimate of wind power Offering less wind power than is expected would be the same as withholding power from the market. As it is usually more expensive for producers to buy extra power when production falls short of predictions than the loss in sales when too little is predicted, it seems natural for producers to promise no more than they can be somewhat certain of being able to deliver, which is then less than the expected value of power generated.

Cautious estimate of water reservoir prospects Production from hydropower plants that rely on water reservoirs, may often be withheld to avoid water shortage later on; which may lead to shortage of electricity with rationing and dramatic increases in prices. Therefore, it seems to be in the interest not only of producers but also consumers that cautious estimates are made of the water reservoirs to minimize the danger of water shortage, and it is thus better to err on the side of caution. But how much to “err" may be a matter of opinion.

Withholding production shifts a part of the supply curve to the right. The part that shifts are all the offerings which were higher than the offer withheld. Under certain circumstances small shifts may cause a considerable increase in the system price when demand is inelastic and more expensive power, than the old system price, must consequently be produced to replace the power withheld.

In order to check whether withholding production may be profitable, tests were run for each of the 7 power players, when their highest, but nevertheless accepted bids in case of full production, were withdrawn. Up to 1000 MWh/h were thus withheld on each player's home market. Sales did not, however, necessarily drop by the same volume, as bids, which otherwise would not have been accepted, were sometimes reduced to minimize production cost.

Figures 10.18 to 10.24 demonstrate the effect on income, cost and profit for the data from Eltra between 11 am to 12 pm on Tuesday, February 11, 2003. Withholding up to 1000 MWh per hour is certainly impossible for some of the players, but the figures give us an idea of what could be accomplished. The income and cost have been divided by 10 in order to give a better view of the profit.

The Danes will lose from withholding production, whereas Statkraft, Vattenfall, Sydkraft, Fortum and E.On will profit. E.On starts to make insignifi-

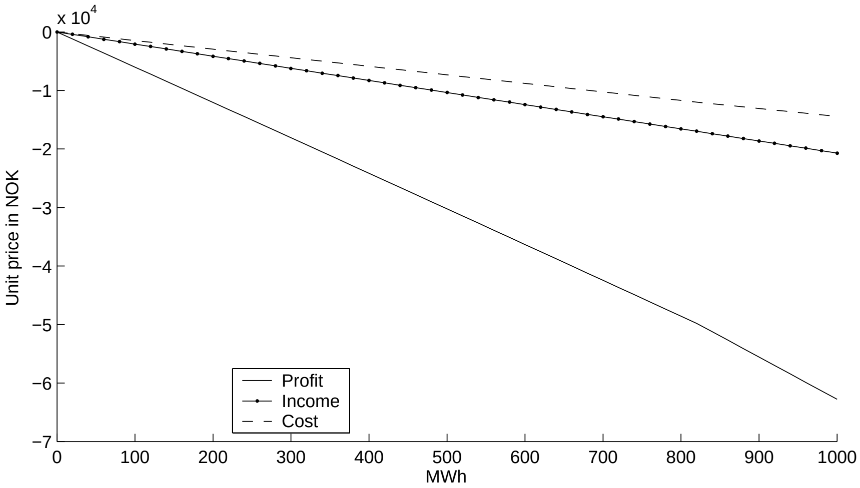

Figure 10.18: Tuesday: Hourly change in E2's profit when production is withheld

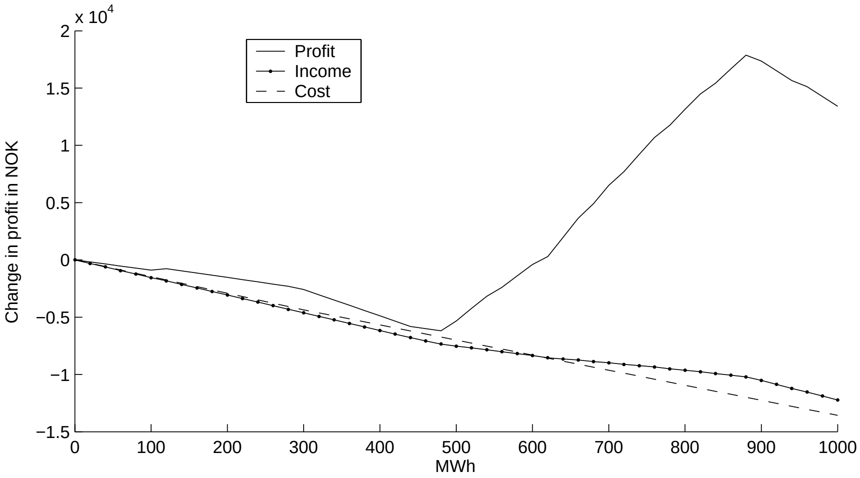

Figure 10.19: Tuesday: Hourly change in Elsam's profit when production is withheld

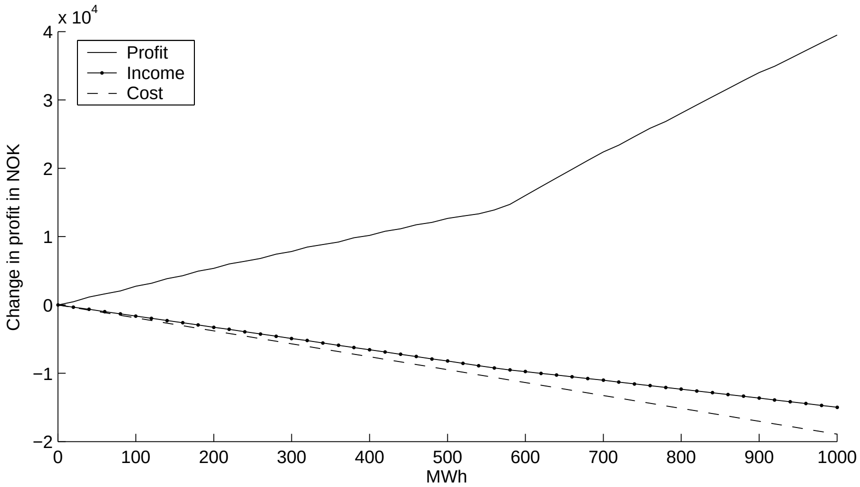

Figure 10.20: Tuesday: Hourly change in Statkraft's profit when production is withheld

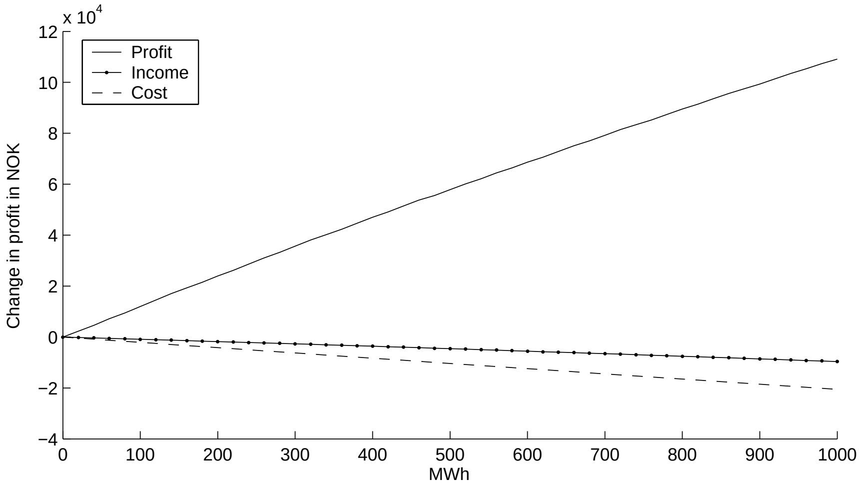

Figure 10.21: Tuesday: Hourly change in Vattenfall's profit when production is withheld

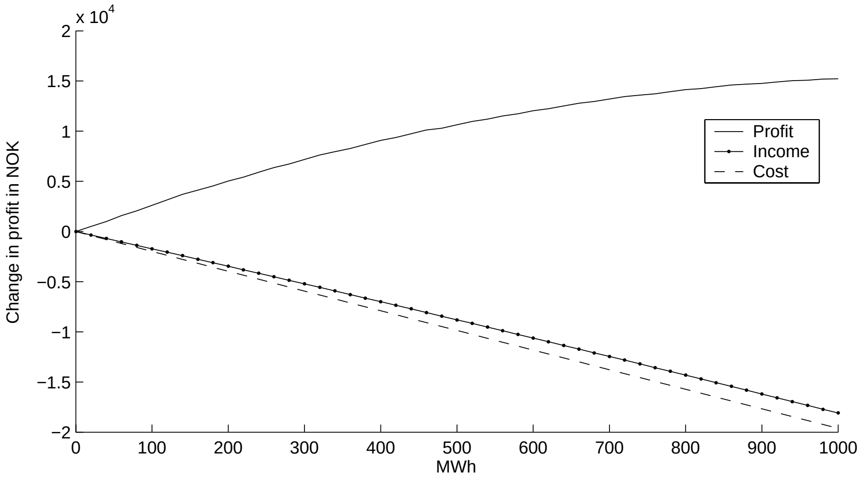

Figure 10.22: Tuesday: Hourly change in Sydkraft's profit when production is withheld

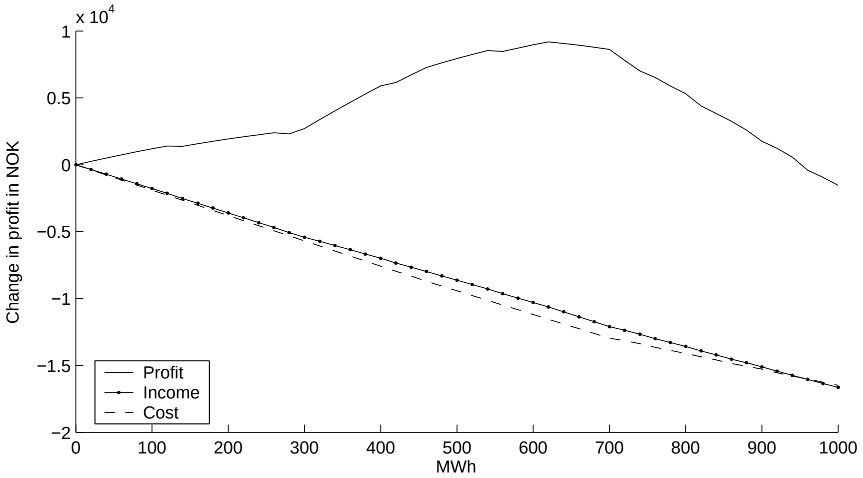

Figure 10.23: Tuesday: Hourly change in Fortum's profit when production is withheld

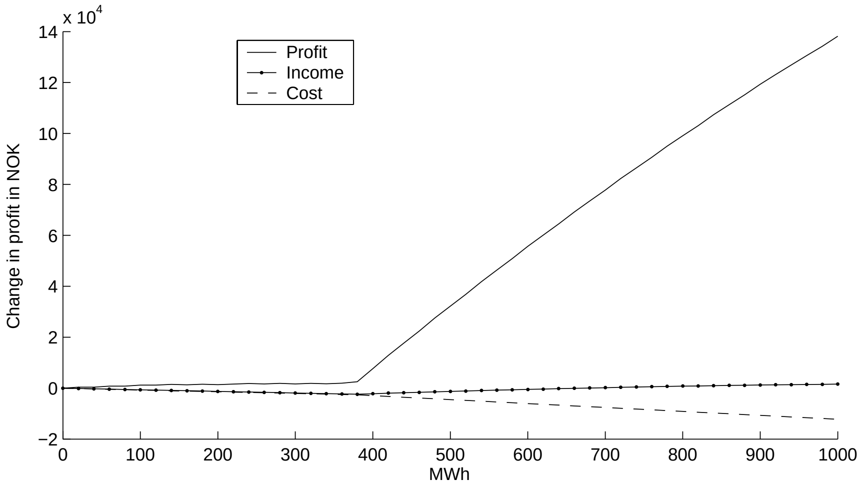

Figure 10.24: Tuesday: Hourly change in E.On's profit when production is withheld

cantly more profit when withholding 400 MWh/h or more.

Figures 10.25 and 10.26 show the profit of each player for the data from the 1^{st} hour of Monday, February 10, 2003.

The Danes start to make a handsome profit when withholding ca. 500 MWh/h; E2 after considerable loss up to that time. Other players make less profit, except Fortum which always seems to lose. Notice the frequent small steps in the profit of Statkraft, Vattenfall, Sydkraft and Fortum.

Withholding wind power will be less profitable than withholding more expensive power, although withholding the latter may be easier. In figure 10.27 the optimal production for can be seen for Elsam at the two data dates. Actual production was 335 and 304 MWh for Monday and Tuesday respectively, windy days, but the dream production for Elsam would be 850 MWh on Monday and even more on Tuesday, both being more than they can deliver with the current installations.

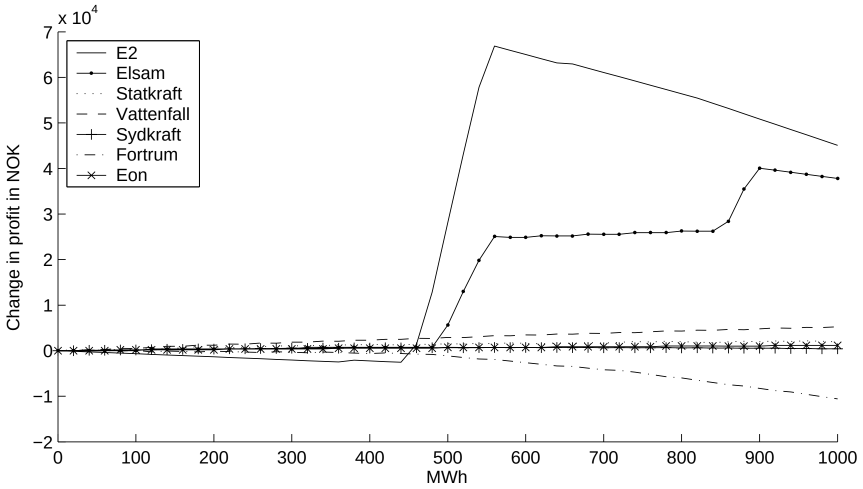

Figure 10.25: Monday: Hourly change in profit when production is withheld

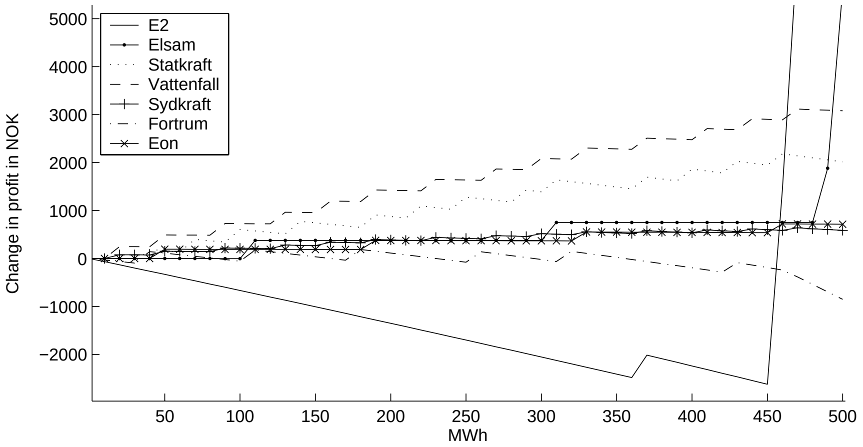

Figure 10.26: Monday: A closer look at profit

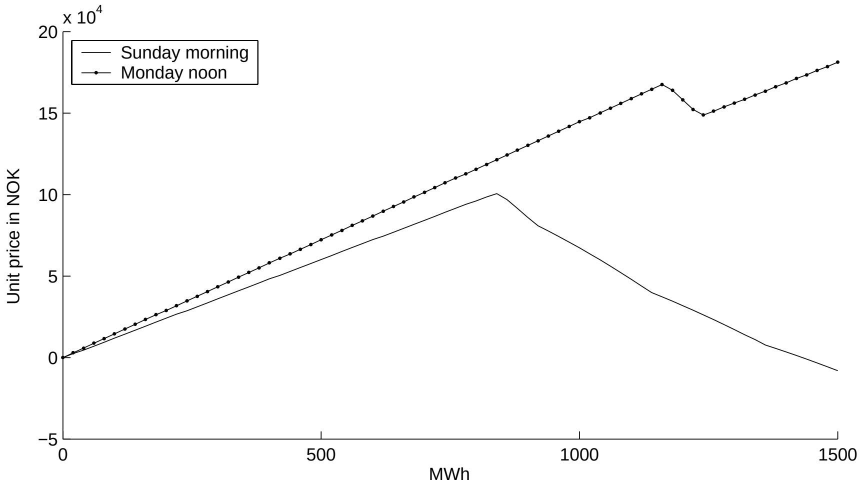

Figure 10.27: Optimal wind power production for Elsam

10.6.3 Wrong predictions

The line between being cautious and imprudent may be difficult to follow. Offering less than expected at the spot market can be accepted to a certain limits, but to what extent? Predictions may always be wrong, but they can also be made wrong.

It is less expensive to be wrong about the water reservoir level than about the wind power. Wind power withheld is lost, blown away, while the water may be kept and put to use later, which may be a drawback to market power users, as this may cause lower prices later on.

Surplus wind power can be put to some use. It can replace the more expensive production of the same player, which in reality allows the player to rate some of his expected wind power, much higher than otherwise, as e.g. expensive gas turbines may be replaced. The surplus may also be sold to other producers who may find it convenient to buy inexpensive power for reselling rather than producing expensive power themselves.

Finally, in Denmark there are plans to use surplus wind power for heating water for central heating. This may lead to a smaller supply of cheap CHP power during the following hours or day when less heating carried out, to the delight of most producers. The use of an unpredictable surplus wind power to heat water requires the existence of large insulated water tanks.

All possible use of cheap surplus wind power contributes to making wind power "predictions" an instrument of market power.

When wind power can be used to replace more expensive production, the effect is the same as when withholding the most expensive production. As can been seen in figures 10.19 and 10.26, Elsam would benefit from predicting 0 instead of the 334 MWh on Monday (and thus withhold 334 MWh of expensive power) but needs to produce more wind power to be able to exploit the situation on Tuesday, and Elsam should therefore put forth a correct "prediction."

10.6.4 Blocking grid lines

One aspect of market power would be to block cheap power from other markets from flowing into the more expensive markets, with the consequent price reduction. If the line between two markets is blocked, this will cause higher a price on one of the markets and a lower price on the other market.

Blocking grid lines will not be as popular with other players as is the traditional exercise of market power, as producers in cheap markets will not be able to sell power abroad, in addition to suffering lower prices on the home market. The blocking player will instead acquire, with other local producers, protection from foreign competition which will increase prices on his market.

In figures 10.28 to 10.30 we see how players' profit would be affected should the grid line between eastern Denmark and Sweden be blocked on Tuesday, February 11, 2003. When the grid line is not blocked, eastern Denmark forms a price area with the northern markets. However, when the line is blocked, prices in eastern Denmark tumble and eastern Denmark becomes its own price area as the cheapest power market, to the delight of Danish consumers, but the wrath of E2. Vattenfall would have the most to gain by the blocking.

Certain changes in regulations regarding reservations of grid lines have recently by made to hinder the blocking of international grid lines. I am not familiar with how blocking can currently be done, and will therefore

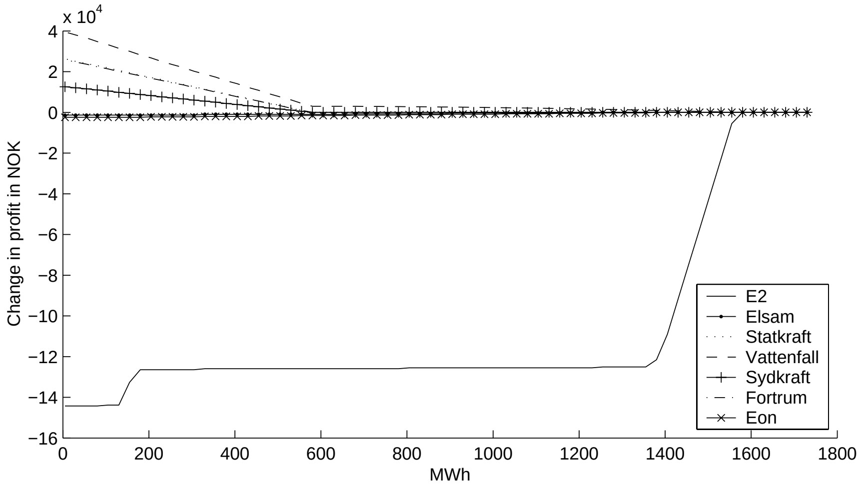

Figure 10.28: Turning off eastern Denmark

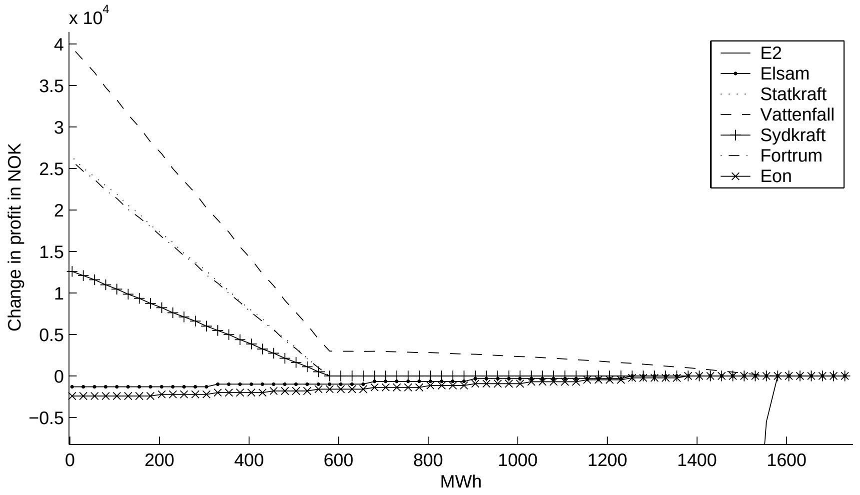

Figure 10.29: A closer look at the Sound connection

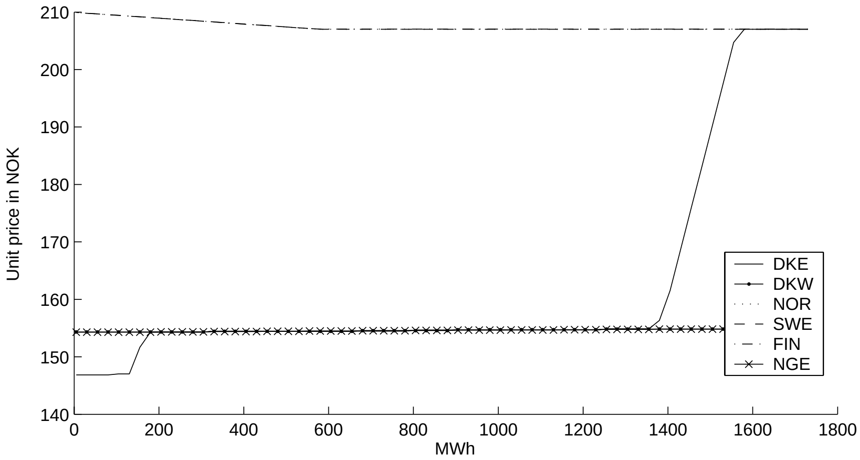

Figure 10.30: Prices when holding up the line

not discuss this method further in this thesis. This has only pointed out as a possibility.

10.6.5 Cooperation

Cooperation between players can be either active or inactive. Active cooperation would include a formal or more likely an informal and secret deal between players concerning market behavior and the division of profit from the use of market power.

Inactive cooperation could be not to use opportunities to lower prices, even though more profit could be gained at least temporarily, or to increase prices in the hope that other players will follow, which would be inactive cooperation from their side.

Cooperation in itself is not market power. However, cooperation magnifies the benefits of using other methods of market power as larger market share and greater price control will be gained and exploitation of the situation from, now fewer, competitors will be reduced.

When examining figure 10.31 where the Tuesday data is used, we can see that Elkraft, which is not one of the power players, would want to produce ca. 500 MWh/h if it is not able to produce at least 800 MWh/h. However, if Elkraft and E2 were cooperating and thought of maximizing their total profit, Elkraft would never want to produce more than 500 MWh/h unless being able to deliver at least 1500 MWh/h.

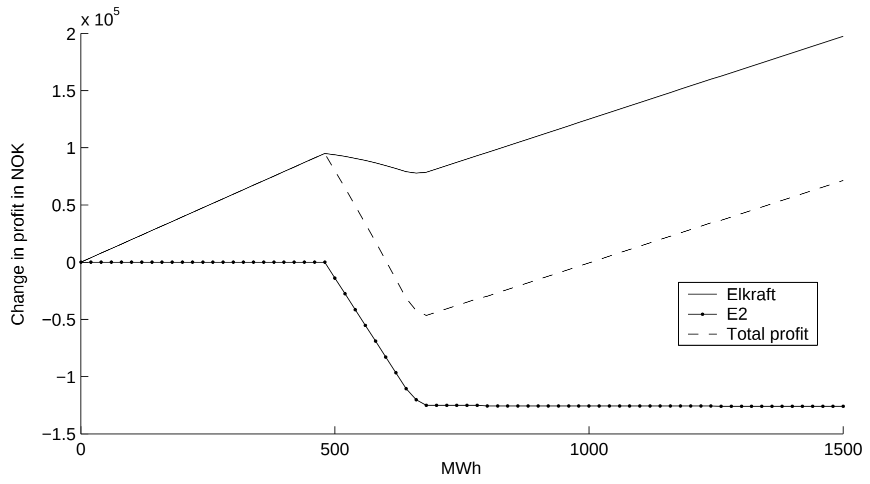

Figure 10.31: Optimal wind power production

10.6.6 Leaving the spot market

By making long term contracts with prominent buyers, a producer can decrease trade on the Nord Pool spot market, although in theory the long term buyers could resell their power on the spot market, and thus make the market more shallow and less liquid, with fewer participants on both sides. According to Nord Pool, trade on the spot market has been increasing in recent years and currently there seems to be no reason for concern regarding decline in trade in the near future.

10.7 Detecting market power

Having defined some of the possible forms of market power, one might be interested in finding out whether any of it is being used.

10.7.1 By whom?

Firstly, one must decide who would be trying to detect the market power. The most likely are those which in section 10.3 were referred to as the 'losers.' These are the foremost:

- Nord Pool
- Transmission system operators
- Competition institutions and authorities

Of the above, Nord Pool is by far in the best position as they are the only party that will know the exact bidding of all the electricity generators. Other parties must be satisfied with filling into the blanks with guesses and models.

The true production cost is then, of course, only available to the power plant owners, making all assumptions of market power based on assumptions of production cost.

Finally, there are the water reservoirs with their complex pricing.

10.7.2 And how?

The following are what detectors should be monitoring:

Outage Does the player benefit? Are outages more frequent than expected?

Size Does the player have a large market share?

Predictions Does the player benefit from predicting too little wind energy? Is there systematic undervaluing in predictions?

Water reservoirs Is the water reservoir situation as critical as hydropower generators may claim?

Grid lines Are grid lines reserved, and, if that is the case, are they being used?

Fuel cost Does the price of electricity from coal, oil and gas sources go up with the price of the raw materials, but not down again?

Price Is the price simply too high compared to models? Are there Nash equilibria or is there cooperation with Pareto optimal solution?

Being alert and searching for pattern in behavior is probably most efficient way of market detection.

Chapter 11

Price strategies

11.1 Overview

There are a few possible circumstances on the market. In the following sections, these will be discussed and analyzed for optimal response. Under all these circumstances the highest accepted bid is the crucial factor as it sets the price and we assume, for simplicity's sake, strict limits to how the supply curve may be manipulated and that no player can reduce his bid to a lower price than any of his other originally lower prices. I.e. he cannot lower two bids to below a price both bids were above before. Having said that, it leaves us with two important bids for each player, his highest accepted bid and his lowest unaccepted bid. If the player holds the highest accepted bid on the market, and the bid is only partially accepted, this bid function as both the highest accepted and the lowest unaccepted bid.

To heighten the market price, a player must increase his highest accepted bid until the bid is either no longer accepted, or only partially accepted. In order to sell more, a player must lower his lowest unaccepted bid to below the highest accepted bid. Whether increasing or decreasing prices will benefit the player depends on his market share, his markup and the elasticity of demand.

11.2 Export and import

When the export capacity between two or more markets is not fully utilized, they have the same price and therefore form a single price area. The same price is on all the markets and they function as a single market until all the transmission capacity has been used, either by lowering or heightening the price of the local supply.

When there is a different price between two markets and there is full use of transmission capacity between them, the supply line of the more expensive market gets the addition of the same volume as the transmission capacity between the markets. The supply of the cheaper market is reduced by the same volume.

Example 11.1 *The market price in Norway is 190 and 175 in Sweden, but would have been 200 in Norway and 165 in Sweden if no export had taken place. This is demonstrated in figure 11.1, where the broken lines represent supply and demand in Sweden after export and the continuous lines are the demand and supply in Norway after import. The dotted line is the demand in both Sweden and Norway before transmission (the same demand is used to keep the diagram less crowded), which is then shifted 100 MWh to the right for Sweden and 100 MWh to the left for Norway as 100 MWh are exported from Sweden to Norway. N1 and N2 are the prices and volume in Norway before and after import respectively, S1 and S2 are the prices and volume in Sweden before and after export.*

This shift of the demand curve will give us the right market price and the correct amount of power produced in each area, but not the correct consumption in each area. If the supply curves had been shifted in the opposite directions, Norwegian to right and Swedish to left, correct prices and consumption could be read from the figure. This is because consumption and production can not be equal in markets where import or export is taking place.

However, this approach of shifting the whole curves is not entirely accurate. It would be more accurate to transfer the most expensive supply produced from the Swedish supply curve and add it to the Norwegian supply curve. There it would form a part of the new Norwegian supply curve, but would cause the same shift to the right at and above the Norwegian market price, as all imported Swedish supply would be cheaper than the market price; as otherwise it would not be imported. Thus, the new Swedish supply can

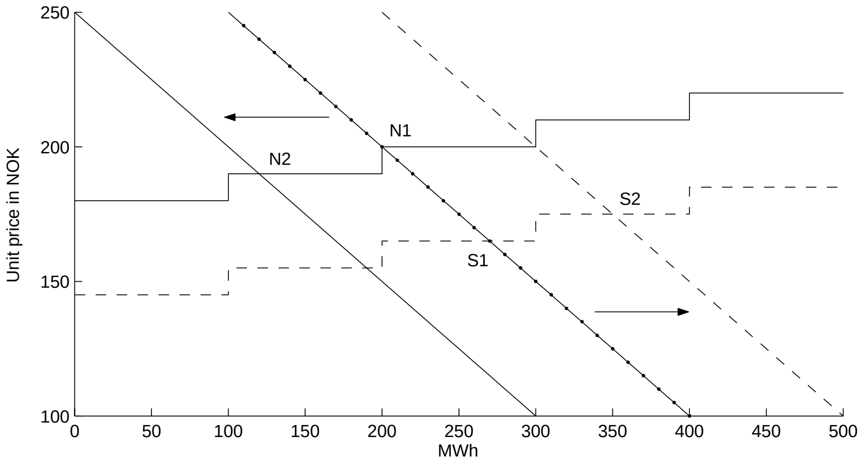

Figure 11.1: Effects of export/import on prices in Norway and Sweden

become the second highest accepted or even the highest (fully, as otherwise there would be the same market price and a single price area) accepted bid on the Norwegian market.

The same is also true for the shift of the Swedish demand when the Norwegians start buying. The part of the Norwegian demand curve immediately to the right of the old market price would be shifted to Sweden to form a part of the new Swedish demand curve. Thus, both Swedish and Norwegian producers only have to take a look at their own modified demand and supply curves and do not have to observe other markets when deciding their own price strategies, as all the important information is to be found on the demand and supply curves in their own price area.

11.3 Selecting a strategy

11.3.1 Highest accepted bid

When a player holds the highest accepted bid, it means that unless he also holds the lowest unaccepted bid, other players may be tempted to challenge this bid. The bid can either be fully or only partially accepted. See figure 11.2.

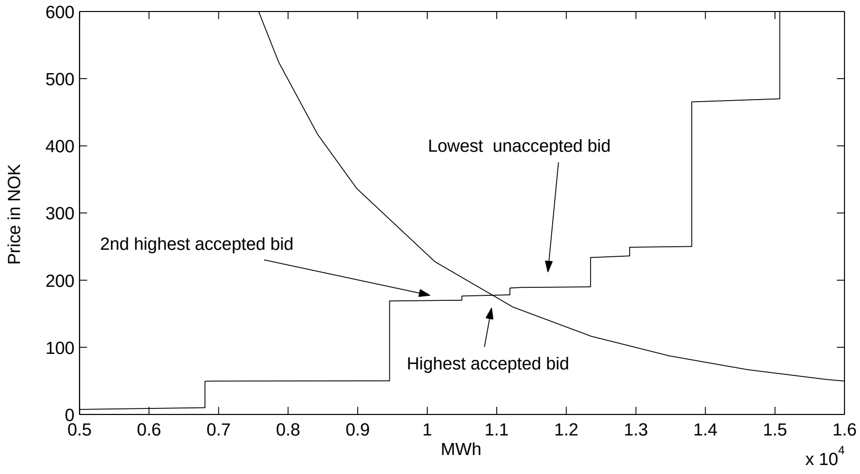

Figure 11.2: Supply and demand on the Finnish market

11.3.2 Fully and partially accepted bids

If the highest accepted bid is fully accepted, as in figure 11.3, the holder of the bid has nothing to gain by reducing his price and thus underbidding other players as he would not be selling any more. He can, however, take advantage of the fact that the market price will not decrease when he lowers his prices and thus reduce the likelihood of underbidding from other players. In order to heigthen the market price, the player must increase prices until not all of his bid is accepted. From there he may increase the market price if profitable. Only when the highest accepted bid is partially accepted will raising or lowering it affect the market price and sales, and thus that player's profit.

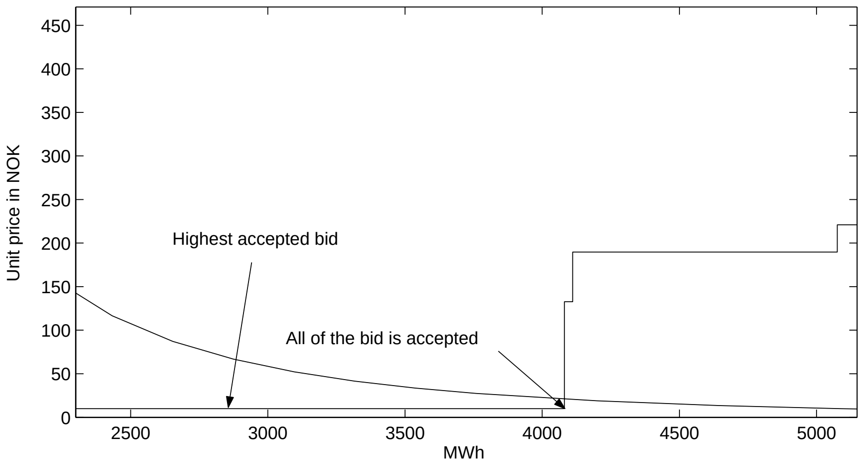

Figure 11.3: Demand and supply in western Denmark

11.3.3 Second highest accepted bid

The holder of the second highest accepted bid is only under threat from the holder of the highest accepted bid, if not all of the highest accepted bid was accepted, as otherwise the holder of the highest bid would have nothing to gain by underbidding nor would the holder of the second highest accepted bid have anything to lose. If possible, that player should lower his bid to below the production cost of the highest accepted bid or at least maintain a gap between his bid and the highest accepted one. He should do so in order to discourage underbidding, especially if a large part of the highest accepted bid is only partially accepted. The holder of the second highest accepted bid can never benefit from increasing that bid while below the market price.

11.3.4 Lowest unaccepted bid

The holder of the lowest unaccepted bid is always in position to challenge the highest accepted bid. If all of the highest accepted bid was accepted, that player can increase sales without underbidding the currently highest accepted bid by lowering his bid to below the market price, but nonetheless staying above the highest accepted bid. That will, however, cause a market price reduction, as will all additional sales. This player could also underbid the highest accepted bid, but he should only do so if his production cost is lower than the production cost of the highest accepted bid, unless the holder of the highest accepted bid is not expected to react.

As the bidding blocks are often quite large, players will always gain by reducing their prices to just below the competitor, until they reach their own production cost, and gain some extra sales as their bid will replace the bid of the competitor. Therefore, players should never try to underbid bids with lower production cost, as this will most likely only cause lower market price while probably selling nothing or just a little more. This is demonstrated in figure 11.4.

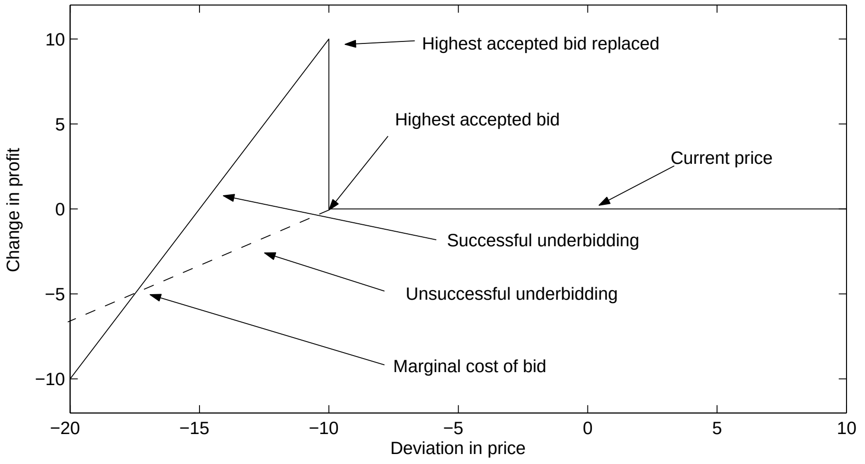

Figure 11.4: Gains and losses for the holder of the lowest unaccepted bid

In figure 11.4, a player holds, in the beginning, the lowest unaccepted bid, defined as zero on the x axis, at NOK 10 above the highest partially accepted bid and the market price, and NOK 17 above his marginal cost. If the player now lowers the price of his bid, his profits will be constant until his bid becomes lower than the highest accepted bid. His profit will then increase, but only if the other player does not in turn lower his price. Hence, there are two profit lines: one showing the player ending with lower bid than the competitor, and the other, the broken one, showing when the competitor prevailing with the lower bid. While the continuous line stays above the broken line, the player will gain by reducing his price to just below the competitor, provided that the competitor has underbid him. Indeed, he will constantly be shifting between the two profit lines as the competitor reacts and counter-reacts, starting a downward price spiral. This is, however, only true until the player reaches his own marginal production cost, as, from that time onward, he will lose more by prevailing with the lower bid and thus sell his power at below marginal cost. Thus, before the player starts underbidding others, he should be certain of being able to win the price war, which is only possible should the competitor either not respond or have higher marginal production cost.

If the highest bid had been fully accepted, the competitor would have been wise to keep his price below the marginal production cost of the player as explained before, as he would not cause a lower market price, while avoiding the price war.

A wiser move for the holder of the lowest unaccepted bid, if he has a higher production cost than the highest partially accepted bid, would therefore be not to underbid the competitor but to increase his price. This may tempt the competitor to raise his price too, leading to higher market price and a higher profit, at least for the player.

This is an example of when a solution that is not a Nash equilibrium but Pareto optimal, prevails.

11.3.5 Power players

If none of the important bids are held by other power players, a player should select the price strategy that maximizes the current profit as no response is expected. (Nash equilibrium).

Part IV

Calculations

Chapter 12

Price calculation algorithms

12.1 The price of everything

In order to be able to simulate the Nord Pool market, a method should to be used that can, given the correct data, calculate the prices, production, consumption, export and import for each market. With such a tool developed, a deviation from the production cost function can be used to simulate market power.

12.1.1 Eltra's method

Eltra has developed a program to calculate the correct market prices on each market, given certain demand and supply curves. Eltra presents this as an integer optimization problem, where the total social surplus is optimized. This surplus is composed of producer surplus, consumer surplus and the grid or the bottleneck surplus. The grid surplus is the profit derived from buying a unit of electricity from a cheap market and selling it to a more expensive one and is administrated by the relevant system operators. This maximization provides the correct results as selling a unit to the one who is ready to pay the most for it, is always optimal and gives the correct quantity of net export and import, given the transmission limitations.

Example 12.1 *If a unit with a production cost of NOK 190 could satisfy a Swedish buyer ready to pay NOK 200, the combined consumer and producer surplus from that sale would be NOK 10. However, if instead of the Swedish buyer, a Norwegian buyer would be ready to buy that unit for up to NOK 220, the consumers and producer surplus with the addition of the grid surplus would be 30.*

Thus, if the cheapest power unit, from all the markets, is always taken and sold to the buyer who is ready to pay the most for it and is able buy it, given that this can only happen when there is a direct connection between markets, we will end up with the optimal solution. This may sometimes mean that units will be returned when the next unit is sold from market A to market B, if B had previously been the net exporter to A.

The beauty behind Eltra's approach is that for each market, due to the supply and demand functions, the correct surpluses, given price, import and export, can always be calculated. However, this needs a little data preparation as the cumulative consumers surplus (CCS), and the cumulative producer surplus (CPS) functions, must be created. we can assume that the production cost of the last unit produced will be either the same as or close to the market price. If the production cost of the first three units is 1, 2 and 3 respectively, using the above assumption, the cumulative producer surplus function would be 0, 1 and 3 ($1-1, 2\times2-(1+2), 3\times3-(1+2+3)$). There can also only be a price difference between areas where transmission is at its maximum, as otherwise there would be the same (or practically the same) price.

Therefore, if $t_{j,i}$ is the export from market i to market $j, Capacity_{i,j}$ is the maximum export capacity from market i to j, $BNS_{i,j}$ is the grid surplus from exporting from market i to j and S and D respectively are the supply and demand functions:

$$y_i = x_i + \sum_j t_{i,j} - \sum_j t_{j,i} \ldots \forall i \tag{12.1}$$

$$D_i\left(x_i\right) \geq S_i\left(y_i\right) \ldots \forall i \tag{12.2}$$

$$t_{i,j} \leq Capacity_{i,j} \ldots \forall i, j \tag{12.3}$$

$$BNS_{i,j} = \left(D_j\left(x_j\right) - D_i\left(x_i\right)\right) \times Capacity_{i,j} \ldots \forall i,j \tag{12.4}$$

$$\max z = \sum_i CCS_i\left(x_i\right) + CPS_i\left(y_i\right) + \sum_{i,j} BNS_{i,j} \tag{12.5}$$

This is a linear integer problem, with two multidimensional variables, x which is the consumption in each market and t which is the transmission between markets. Although y is presented as a variable, it is simply the sum of the other two. This is, in fact, not Eltra's presentation of the problem but a simpler one to understand, although built on the same principles and requires more computer power for the optimization.

Eltra begins by calculating the prices and surpluses for each market when there is no international transmission and then creates the CCS and CPS as functions of net import or export as well as the price function P. Therefore, when there is import, CCS increases but CPS decreases. More precalculations are required, as demand and supply must be compared for every possible magnitude of import/export for each market.

$$x_i = \sum_j t_{i,j} - \sum_j t_{j,i} \ldots \forall i \tag{12.6}$$

$$t_{i,j} \leq Capacity_{i,j} \ldots \forall i,j \tag{12.7}$$

$$BNS_{i,j} = \left(P_j\left(x_j\right) - P_i\left(x_i\right)\right) \times Capacity_{i,j} \ldots \forall i,j \tag{12.8}$$

$$\max z = \sum_i CCS_i\left(x_i\right) + CPS_i\left(x_i\right) + \sum_{i,j} BNS_{i,j} \tag{12.9}$$

Here, there is only a single multidimensional variable, t, as x_i, now net export from market i, is only the sum of some of the elements of t.

Eltra's algorithm is written in the optimization program language GAMS.

12.1.2 IMM's verification algorithm

To verify whether Eltra's GAMS algorithm was giving the correct results given the data, a matlab algorithm had been developed at IMM.[1]

As with Eltra's algorithm, the data has to be prepared, and vectors for supply and demand have to be created. The vector's index number is the volume and the vector's value is the price. Interpolation is used to fill the over 26 thousand long vectors for each market, which is the maximum volume offered on the largest market, Sweden. Therefore, the problem is solved discreetly with each MWh/h as the lowest unit, which seems to be satisfactory as the lowest equilibrium is around 5000 MWh/h.

The IMM's algorithm solved the problem in the following steps:

1. Calculate prices for each market by comparing where there is least difference between the supply and demand vectors.
2. Find all possible legal transmissions of one MWh from any market to another.
3. Transfer one MWh from the cheapest market to the most expensive market than can receive transmission from it.
4. Repeat from step 1 until there is no legal transmission available.

The algorithm did confirm Eltra's results, but the calculation time, four days for each trading hour, on IMM's server Sunfire, made it rather limited tool for analysis. [27]

12.1.3 Revision

In order to speed up the calculations, I made some changes to IMM's algorithm. The following are the foremost:

- Allowed more than 1 unit to be transmitted each time; now the algorithm now usually begins with 1000 units.
- Used pointers (as in C++) instead of changing the long vectors.
- Exploited the fact that when x units are sent from market A to B, the new equilibrium is less than or equal to x units away from the old equilibrium. Therefore, only a small part of the supply and demand vectors had to be compared.

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[1] The Department of Informatics and Mathematical Modelling at the Technical University of Denmark (DTU).

- Skipped a number of unnecessary repeated calculations as previous results could often be kept and reused.

I also made it possible to use a unit larger or smaller than 1 MWh as the basic unit. However, I do use the 1 MWh as the basic unit. Although, there is not much left of the original algorithm, the four steps listed in section 12.1.2 are there as before, except that more than one unit can now be transmitted. After a thorough revision, each cycle of calculations now takes approx. 0.05 seconds on Sunfire, without the data preparations. This is a considerable improvement and makes this algorithm the fastest of the three mentioned and will therefore be used hereafter. The new algorithm can be found in appendix B.1 and has the following main steps:

1. Calculate prices for each market by comparing where there is least difference between the supply and demand vectors.
2. Find all possible legal transmissions of one MWh from any market to another.
3. Transfer x MWh from the cheapest market to the most expensive market than can receive transmission from it.
4. Repeat from step 1 until no legal transmission available, otherwise reduce x.
5. Repeat from step 1 until there is no legal transmission available or $x < 1$.

12.2 Transmission between markets

It is worth bearing in mind that even though the most effective approach is to transmit power from the cheapest market to the most expensive, the correct prices and net import/export will eventually be reached, while units are transmitted from any cheaper markets to a more expensive one. The exact order of transmission will not affect the final solution although it may take longer to get there. However, the international power transmission, which may emerge from such an approach, may be different from an 'optimal' transmission as there can be many combinations of transmissions for the solution.

Example 12.2 *If Sweden sends 100 MWh to Norway, which in turn sends 150 MWh to Denmark, more economical solution would be for Sweden to* *transmit 100 MWh to Denmark and for Norway to transmit 50 MWh to Denmark.*

As the final results, regarding price, consumption and production, will not change, transmission between markets can be minimized with the following optimization model, where $NEWt_{i,j}$ is a positive variable with minimum transmission, $Capacity_{i,j}$ is the maximum transmission allowed from market i to j and $t_{i,j}$ is the current transmission solution acquired from any of the three algorithms:

$$NEWt_{i,j} \leq Capacity_{i,j} \ldots \forall i,j \tag{12.10}$$

$$\sum_j NEWt_{i,j} - \sum_j NEWt_{j,i} = \sum_j t_{i,j} - \sum_j t_{j,i} \ldots \forall i \tag{12.11}$$

$$\min z = \sum_{i,j} NEWt_{i,j} \tag{12.12}$$

However, the exact transmission of electricity between the markets has no bearing on studies of market power and any optimization of transmission therefore skipped in the calculations.

12.3 Preparing the data

To be able to run the algorithms described in this chapter, the data has to be prepared into vectors where the volume is the index number and the vector's value is the price. The data comes from Eltra and is described in section 8.1.

As supply is given as many small supply curves, one curve for a group of one or more identical plants, they must be united for each market and a single supply curve created and sorted in ascending order. It is also important to keep records of which plant each unit comes from, so the ownership and plant type can be identified. Therefore, whenever the sequence of the combined supply curve is changed, so must the sequence of the information vectors. In appendix B.2, a matlab code for the creation of the relevant supply and demand curves can be found. The preparation of data takes quite longer than the actual calculations of prices based on the prepared data. However, the data is only prepared once for each simulation, while price calculations may be performed more often.

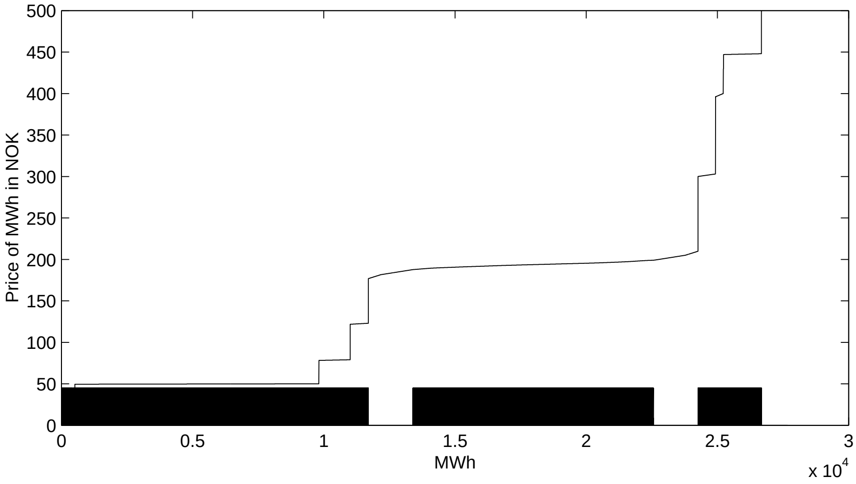

Figure 12.1: Sydkraft and supply in Sweden

The upper line in figure 12.1 shows supply in Sweden. The lower "line" takes the value 40 when Sydkraft owns that unit, otherwise 0. Thus, Sydkraft owns some of the bids in the shaded areas, as the lines between 0 and 40 are so dense that they form black squares.

Chapter 13

Search algorithms

13.1 Nash equilibria

If there is a Nash equilibrium on the market, it indicates that market power is possibly being used, but cooperation between players may be minimum. An exception to this is when, in active competition, selling at the same price as production cost may be a Nash equilibrium. As can be seen from table 7.3, if players begin with low prices or are being underbid, the competition will lead the players to a Nash equilibrium at, or very close to, the production cost. By calculating the prices and profit for each of the 7 power players and then checking whether that player will benefit from changing his strategy, we can find out whether the current situation is either a Nash equilibrium or sufficiently close to one.

According to John Nash, every finite strategic-form game has a mixed strategy equilibrium. However, due to the restrictions on market behavior, only pure strategy equilibria are of interest as mixed strategy requires constant changes in prices. Pure strategy Nash equilibria do not necessarily exist, but they can still be searched for.[25]

There are several ways in which to search for pure strategy Nash equilibria. One of them would be to search from discreet strategies, e.g. allowing markup of players to range from 0 to 10% with steps of 0.5%, or 21 steps in total. Another would be to search for the best strategy by extending the search around the best discreet solution and thus get a “better” solution without increasing computation time too much. As expected, smaller steps made the finding of a Nash equilibrium more difficult as it restricted the options of players to react when underbidding each other and therefore creating mixed strategy equilibria instead of pure strategy equilibria.

Changing the markup does, however, take almost half as long as does calculating prices, so checking a solution with a new markup takes ca. 0.075 sec.

13.1.1 All solutions

Searching for all solutions can be very time consuming as the possibilities can be as many as s^p solutions are possible, where s is the number of strategies available to each player and p is the number of players. Therefore, for the 21 possible strategies described in section 13.1 and with 9 players, as both Fortum and Vattenfall could have different strategies for their markets abroad, there are 794,280,046,581 possible solutions and consequently it would take an eternity to get through them all. Fortunately, there are ways to considerably reduce the number of possible solutions, though many will still remain:

- Identify which markets can form single price areas. With 10% maximum markups, prices in each market can be raised up to 10%, but most likely somewhat less. The maximum price on each market can be found when all players use maximum markup. The minimum price is when there is no markup. Therefore, the problem can be divided into a few smaller problems, one for each possible price area and with a more limited number of strategies for certain players, as only few of their strategies may make them a part of a price area.
- Identify whether players can, indeed, influence their profit through their strategy. In order to be able to do so, they must have bids close enough to the highest accepted bid as described in section 10.6.1. If unable to influence prices, either the player or part of his strategies can be eliminated.
- Identify whether there are reasons to estimate whether some strategies will ever be optimal for a player. These strategies could be eliminated. This can be done by running that player’s strategies against a number of possible discreet area prices. This can eliminate a number of strategies for each player.

- Start by using fewer strategies for each player, followed by searching more closely near the solutions that were the most promising after the first search.

Example 13.1 *If Norway, Sweden and Finland form a single price area, less than 200 thousand combinations of solutions are available for that area, and it may take up to 4 hours to calculate all of them. If Germany and eastern Denmark formed another price area, that would add approx. 15 minutes, and western Denmark could be finished in two seconds. Accordingly, the calculation time would be approx.* $4\frac{1}{2}$ *hours instead of 1,800 years had all solutions been considered.*

When searching for Nash equilibria over a longer period than merely one hour, it becomes more difficult to reduce the number of solutions. Different price areas will continuously be formed and strategies that do not work during day may work at night or at the weekend etc.

As a result, Nash equilibria were not pursued further by this approach.

13.1.2 Iterative search for Nash equilibria

Another approach is to start somewhere, e.g. with no markup for all players, and then try to 'walk' into a Nash equilibrium. This I did with the same maximum 10% markup and the steps of 0.5% as before. A player was randomly selected and his optimal strategy selected. Then another player was selected until no player could select a new strategy or after a certain number of iterations.

Selecting the best strategy is not as simple as may be expected. Sometimes, several or even all strategies give a player the same results. However, the actual selected strategy may influence the future strategies of other players. Selecting the lowest markup decreases the probability of a hostile underbidding, while selecting the highest markup, increases the probability of someone else increasing his bid in the future as discussed in section 11.3. A player could even choose the central optimal strategy or randomly choose one.

And from where should the search begin? One could begin at the 0 markup point, or another randomly selected combination of markups. One must also bear in mind that even if there were a pure strategy Nash equilibrium, it may only be approached from a very small area around it, as mixed strategy equilibria may jealously guard other approaches, in the same way as local maximum may barr the way to global maximum.

The algorithm I wrote for this search can be found in appendix B.3 and consists of the following main steps:

1. Randomly select a player on a market where he operates.
2. If the price on the market has not changed since the last time, that player was selected on that market, remove him temporarily from the player pool and go to step 1.
3. Add different markups to the selected player's bids, sort the supply curve, and calculate his profit and prices on all markets.
4. Select best markup and calculate profit of other players.
5. Remove the player from the pool and return all other players who operate on markets where market price has changed, to the pool.
6. If no player is left in the pool or after certain number of iterations, terminate the process.
7. Otherwise repeat from step 1.

I used this algorithm in all searches for Nash equilibria.

13.1.3 Hourly Nash equilibria

The data in figures 13.1 to 13.5 is gathered, as so often before, from the early morning of Monday, February 10, 2003. The maximum markup for each player was 10%, beginning with 0% markup with discreet strategies running at every 0.5%. When viewing the profit as a function of markup, one can see that the profit curve is not a very smooth one, see figures 13.1 and 13.2. Therefore I decided not to use any search algorithm that could become stuck in a local maximum, but to pursue the equal spacing search.

The highest markup was selected when different markups gave the same profit. A Nash equilibrium was obtained after only 22 iterations, although it took 6 more for the algorithm to terminate. For this data set, this was the fastest termination. In another run with the same data and parameters, the algorithm terminated after 300 iterations without a pure strategy Nash equilibrium, but after a repeated pattern as can be seen in figure 13.6.

Example 13.2 *Player B responds to strategy A_1 from player A by selecting strategy B_2 instead of B_1. Now player A selects strategy A_2 as his response to the new B_2 strategy, which now makes strategy B_1 optimal for*

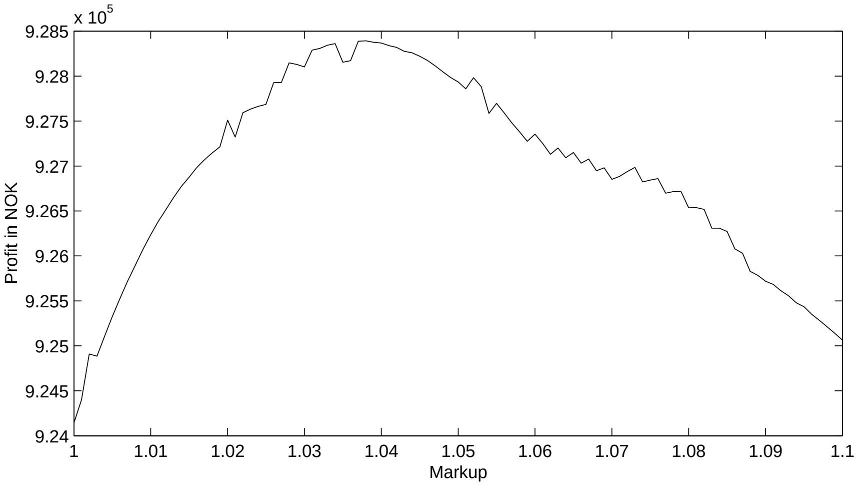

Figure 13.1: The rough reality of profit

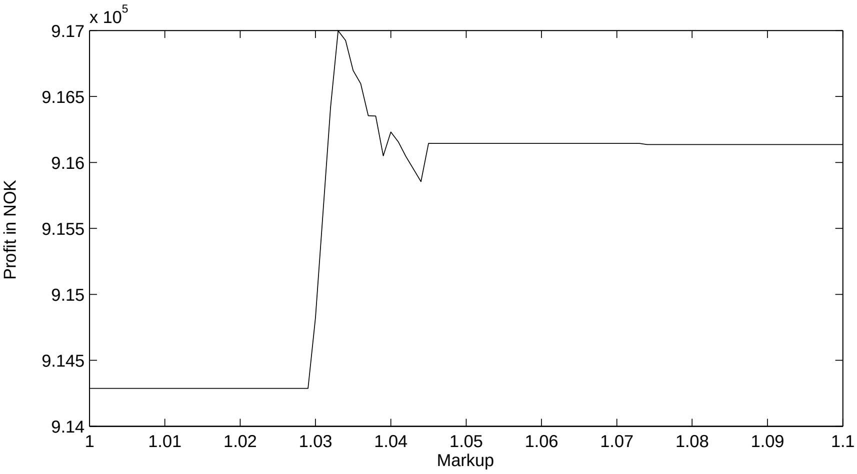

Figure 13.2: Batman's head?

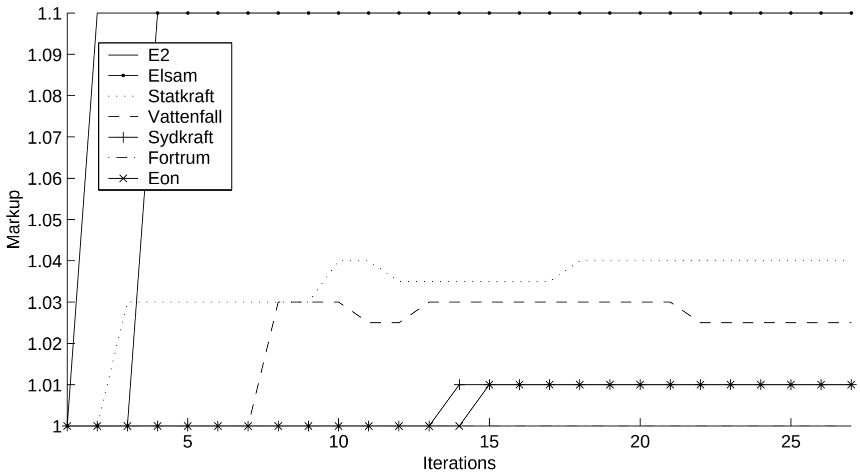

Figure 13.3: Suggested markup of production cost

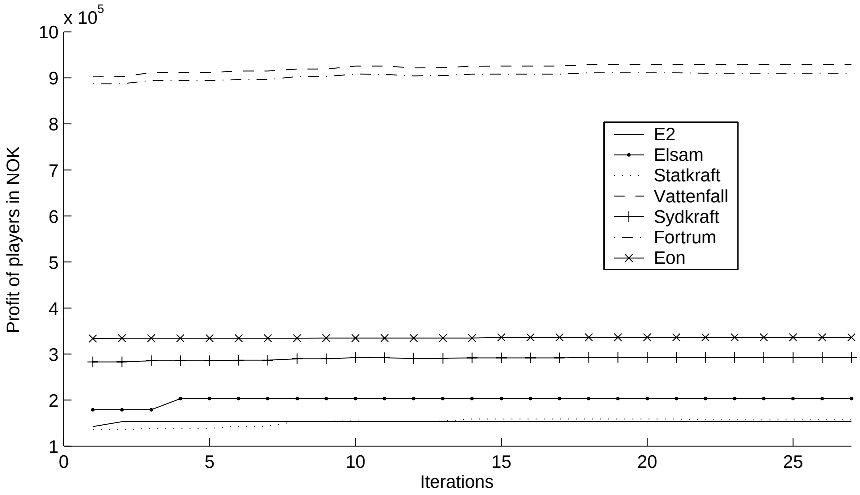

Figure 13.4: Profit of each player

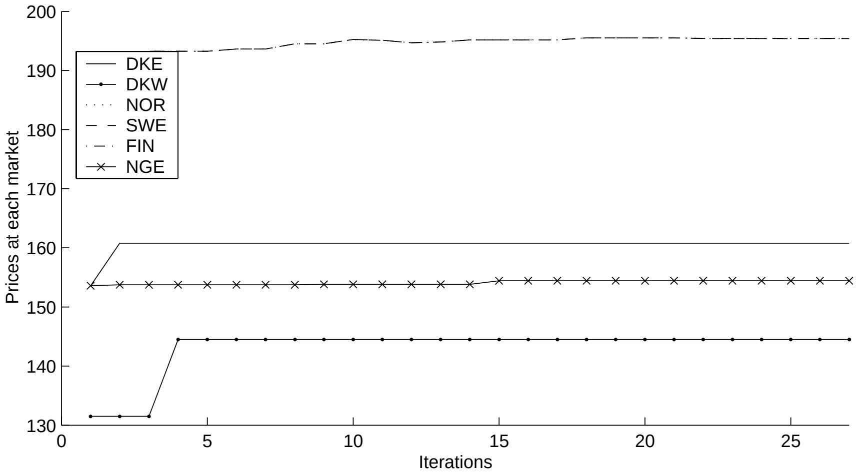

Figure 13.5: Prices on each market

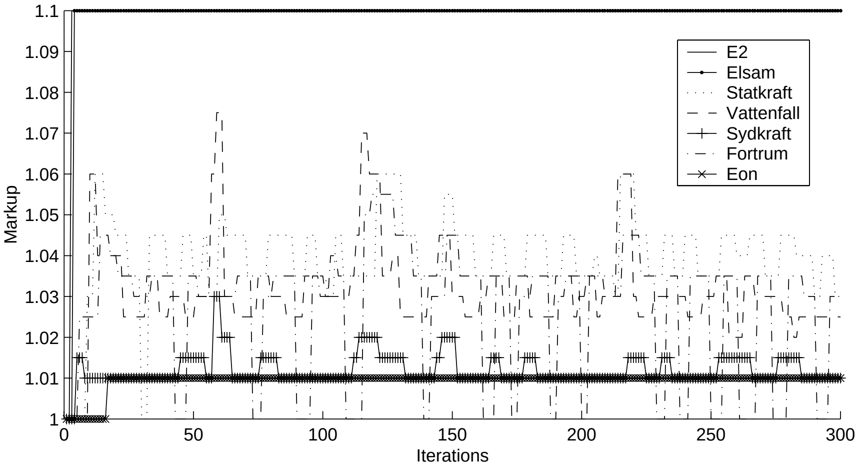

Figure 13.6: The never ending story

player B. Player A then responds with strategy A_1 and the circle goes on and on.

More interesting is to view yet another run, with the same data, as shown in figures 13.7 to 13.9. Here the algorithm terminates after ca. 90 iterations with a slightly different Nash equilibrium than in figure 13.3. In addition to showing that more than one Nash equilibrium can be found, there was a solution in the 43^{rd} iteration, which was Pareto optimal to all found Nash equilibria and with considerable more profit for the northern players. Regrettably, bearing in mind the final equilibrium, Fortum, in this example, could increase their profit by a little underbidding, starting a downward price spiral and ending with each of the northern players acquiring only ca. 1/3 of the market power profit, they could have earned. If Fortum actually had complete information of all bids, production cost and markups of the other players, would they not have stopped there? Even without any cooperation with the other players, it would have been wise for Fortum to stop there. For producers, Pareto outshine Nash just as monopoly outshines oligopoly.

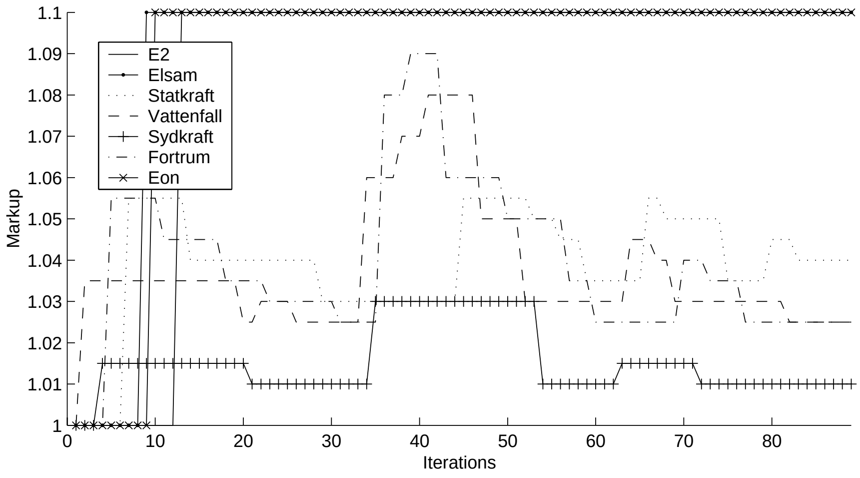

Figure 13.7: The Finnish gambit

The Tuesday data produced rather boring results. After few iterations, the same Nash equilibrium was always found, in which all markups are raised

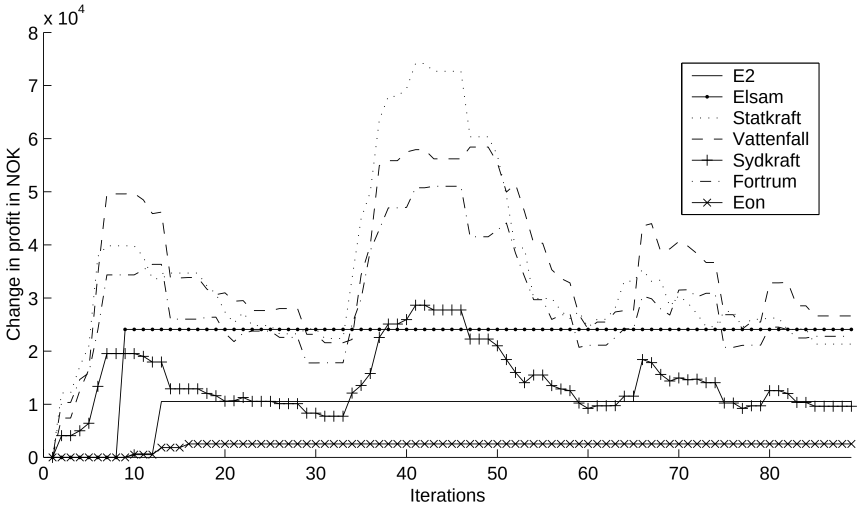

Figure 13.8: Mountain of money?

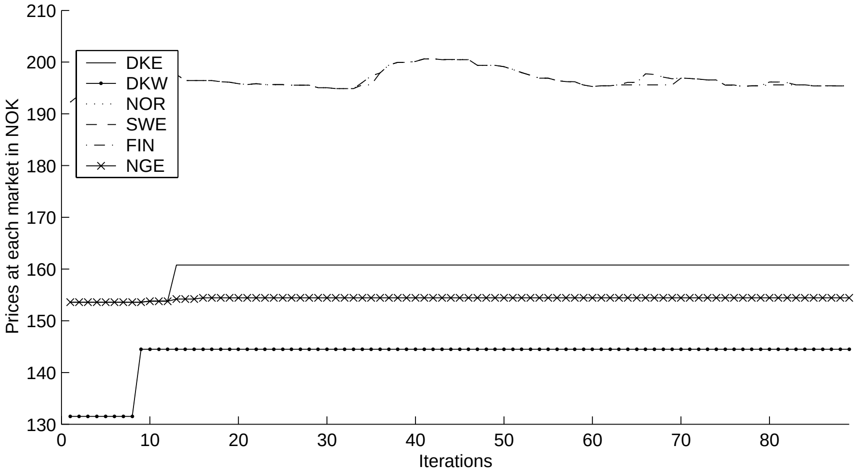

Figure 13.9: The final price to pay for the competition

close to maximum, resulting in higher market prices on all markets. Figure 13.10 demonstrates the results.

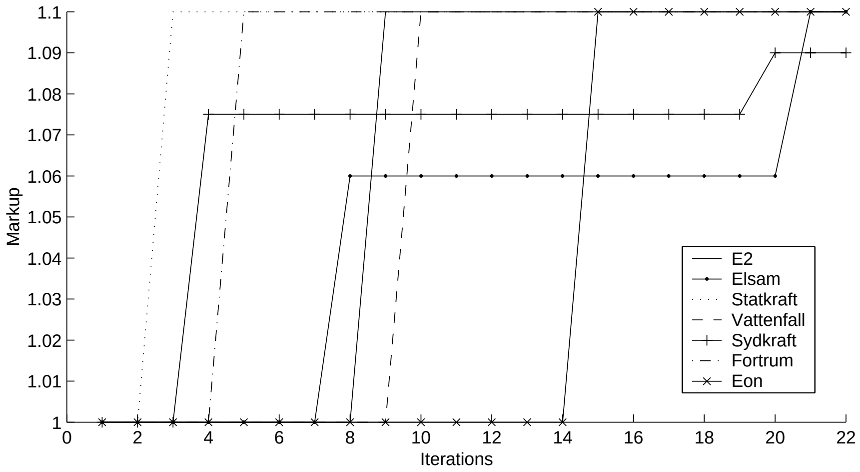

Figure 13.10: Iterated markup on Tuesday

13.2 Pareto optimality

A situation involving a Pareto optimality, or at least a more Pareto efficient solution than the 'natural' Nash equilibrium, would indicate that not only is market power being used, but cooperation, either active or inactive, is also taking place between the players. This may produce considerably higher prices than the oligopolistic Nash equilibria, as monopolistic profit can be gained from a more "restrained" competition.

In order to search for Pareto optimality, only slight modifications need to be done to the search methods for the Nash equilibria.

1. Randomly select a player on a market where he operates.
2. If the price on the market has not changed since the last time, that player was selected on that market, remove him temporarily from the player pool and go to step 1.

3. Add different markups to the selected player's bids, sort the supply curve, and calculate his profit and prices on all markets.
4. Select the best markup.
5. Remove the player from the pool and return all other players who operate on markets where market price has changed, to the pool.
6. If no player is left in the pool or after certain number of iterations, terminate the process.
7. Otherwise repeat from step 1.

The question remaining is, what the best markup would be, as mentioned in step 4.

As there can be quite a large number of Pareto optimal solutions for each Nash equilibrium, some, at least those with local maximums, can easily be found. Therefore, one will have to specify which attributes of the Pareto optimal solution one seeks.

A Pareto optimal solution must be fair to the players, although certainly not to their customers, thus preventing a player, who would have wanted a more profitable solution for himself, from seeking another solution. As most Pareto optimal solutions are not Nash equilibria, the temptation to do so may be great, especially if the player in question has reasons to expect a more profitable solution around the corner.

I considered and tried out three methods for finding Pareto optimal solutions from different starting points, using the same approach as in the search for Nash equilibria:

1. The strategy chosen is the one that maximizes the profit of the current player, while being more Pareto efficient than the last solution.
2. The strategy chosen is the one which maximizes the total profit of all players, while being more Pareto efficient than the last solution.
3. The strategy chosen maximizes the total profit of all players. This is repeated until no better solution can be found. Then the last solution is checked to see whether it is more Pareto efficient than any known "natural" Nash equilibria.

When maximizing the total profit and subsequently comparing the result to the 0 markup, both the Tuesday and Monday data gave the maximum markup as the most profitable for all players. The change from the Tuesday data was that Sydkraft was now using 10% markup instead of 9%, causing their profit to fall while the profit of the other northern players increased more than Sydkraft's loss. The Monday data caused the profit of the northern players to increase dramatically and presented all players with the same profit as or more profit than any Nash equilibrium found. By comparing figures 13.8 and 13.11 it can be seen that even the profit peak discussed previously is dwarfed by the profit the northern players can attain.

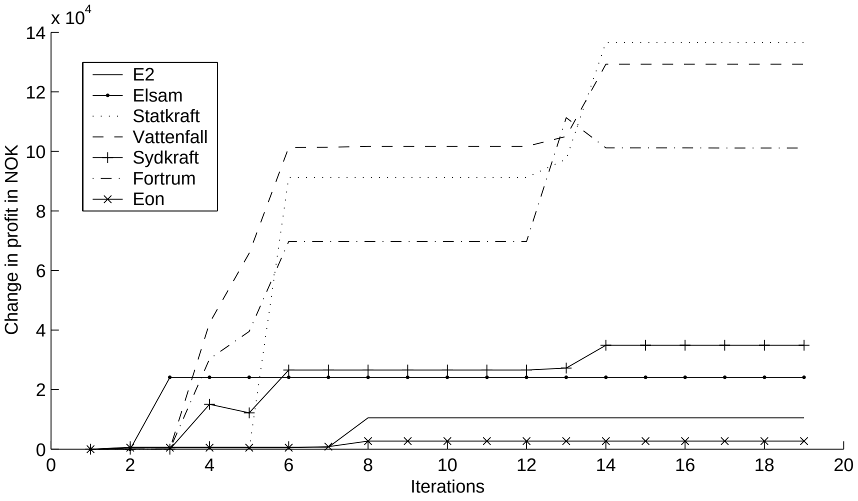

Figure 13.11: Pareto on Tuesday

However, as can be seen in figures 13.12 and 13.13, the newly acquired profit is not a Nash equilibrium as 'greedy' Fortum (again) makes a short term profit by dropping the price in Sweden. The good Pareto optimal solution becomes the victim of competition which ends in a Nash equilibrium with far less of a profit for the northern players.

13.3 Simulating annealing

Simulated annealing (SA) is a generalization of a Monte Carlo method for examining the equations of state and frozen states of n-body systems.[29] The concept is based on the way in which liquids freeze or metals recrys-

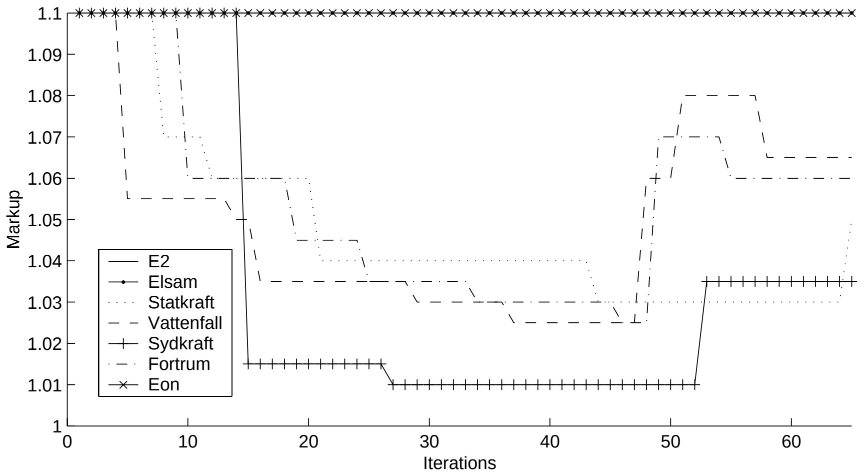

Figure 13.12: A new Finnish gambit

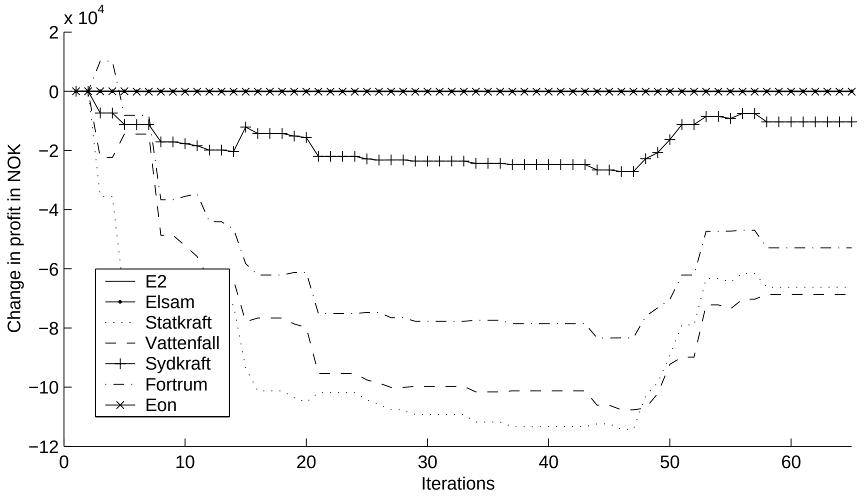

Figure 13.13: All is lost

talize in the process of annealing. In an annealing process a melt, initially disordered and at a high temperature, is slowly cooled so that the system at any time is approximately in thermodynamic equilibria. As cooling proceeds, the system becomes more ordered and approaches a "frozen" ground state at T=0. Hence the process can be thought of as an adiabatic approach to the lowest power state. If the initial temperature of the system is too low or cooling is not done sufficiently slowly, the system may become quenched, forming defects or freezing out in metastable states (i.e. trapped in a local minimum energy state). The original Metropolis scheme was that an initial state of a thermodynamic system was chosen at energy E and temperature T, holding T constant, the initial configuration is perturbed and the change in energy dE is computed. If the change in energy is negative the new configuration is accepted. If the change in energy is positive it is accepted with a probability given by the Boltzmann factor exp -(dE/T). This process is then repeated for a sufficient number of times to give good sampling statistics for the current temperature, and then the temperature is decremented and the entire process repeated until a frozen state is achieved at T=0.

By analogy, the generalization of this Monte Carlo approach to combinatorial problems is straight forward.[30][31] The current state of the thermodynamic system is analogous to the current solution of the combinatorial problem, the energy equation for the thermodynamic system is analogous to the objective function, and the ground state is analogous to the global minimum. The major difficulty (art) in implementing the algorithm is that there is no obvious analogy of the temperature T with respect to a free parameter in the combinatorial problem. Furthermore, avoidance of entrainment in local minimums (quenching) is dependent on the "annealing schedule", the choice of initial temperature, how many iterations are performed at each temperature, and how much the temperature is decremented at each step as cooling proceeds.[28]

13.3.1 Application of simulated annealing to find Nash equilibria

SA is a powerful optimization heuristic algorithm. In one of my programs, I gave each players opportunities to sometimes select a different markup than the optimal one. However, instead of using SA, I found more efficient to randomly select different starting points and walk the 'straight' way into some mixed or pure strategy Nash equilibrium. This was partially because, there often is no way to tell whether one Nash equilibrium is 'better' than another. Hence, the main benefits of SA, finding global maximums, were not exploited by its application for the Nash equilibria search.

13.3.2 Application of simulated annealing to find Pareto optimality

I also used SA to search for Pareto optimal solutions, but later discovered the futility of such a search as the maximum markup was usually found to be the 'best' Pareto optimal solution.

Therefore, the use of SA did not contribute very much to the searches, although it may be practical under certain circumstances.

13.4 Longer periods

In the previous sections I have discussed methods for finding Nash equilibria for a single hour. However, as discussed in section 10.6.1, changing the price strategy to meet hourly prospects is almost impossible. Players would therefore have to find longer periods, on which to base their strategy.

13.4.1 Cycles

A strategy must be based on a kind of cycle which is repeated. The smaller the cycle is, more profit can be gained as the strategy would be tailored to a short period. However, small cycles also require a finer control of prices, which can be difficult to maintain due to market surveillance. Longer cycles are therefore easier to maintain but will not fit so well to each hour of the cycle. It is also more difficult to calculate the best strategy for longer periods as more data must be processed.

Days form a cycle as consumption is less during the day than the night. However, every week has a weekend with a considerably different demand, which would require changes to be made every week, an obviously impractical endeavor.

Weeks form a whole cycle with five high demand working days and two low demand days at the weekend. However, weekly cycles do not cover seasonal changes in demand, which means that changes must be made to the strategy in the course the year.

Years form a cycle with full seasonal changes. Years should only differ from each other as being either very cold or very warm and either very wet or very dry.

Longer weather periods due to climate changes or special weather phenomenona like El Nino and global warming, can form a cycle. It is probably rather impractical to build a strategy based on such a long and unpredictable periods.

Weeks may be the most convenient size of cycle, as small changes in price strategies might trickle through with new seasons. In the following sections I will focus on weekly cycles.

13.4.2 Weeks

To find the optimal strategy for a week, one must find a strategy that weighs five working days strategies with two weekend days strategies. The data from Eltra does form a single week, actually with different a supply function for each hour, with the wind power being the main source of deviation. The Monday and Tuesday, to which I have referred in several previous examples, were in fact fairly windy days, with quieter days to follow.

However, it takes much more computer power to optimize a strategy based on a whole week as opposed to a single hour. There are 168 (7 × 24) hours in a single week, which is the factor of increased computer time and memory usage needed in comparison with hourly calculations.

13.4.3 Nash and Pareto

I made some modifications to the search algorithms I used to find hourly Nash equilibria and Pareto optimal solutions, to include the total profit calculations for each markup for the whole week.

In order to decrease computation time, I reduced the number of strategies available for each player by increasing the step length between available markup options from 0.5% to 1%. Despite these changes, a huge amount of RAM[1] was needed as four $27,000 \times 6 \times 168$ sized matrixes had to be maintained during the calculations, which is too much for most personal computers. Each iteration took from between four to six minutes, depending on the load on the Sunfire server.

With each search taking several hours, the number of searches made, was limited, considerably. However, three results will be demonstrated.

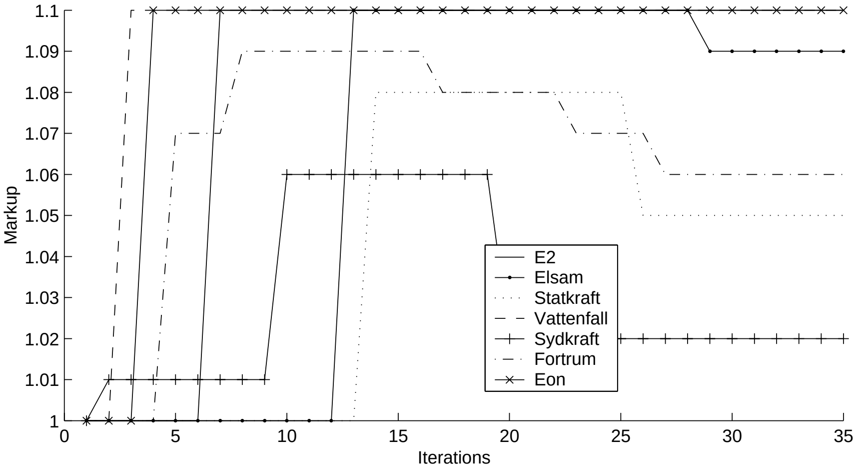

Figure 13.14: Whole week Nash equilibrium from 0 markup

The Nash equilibrium found in the search illustrated in figures 13.14 and 13.15, was found after relatively few iterations, albeit after a long time. The larger step size in markup may have contributed to the few iterations or even the finding itself. The change in profit is of course far more than in the previous examples as it is the combined profit for the whole week instead of only a single hour. E2, Vattenfall and E.On pursued a maximum markup strategy while the other players were satisfied with lower markup.

I made another search from a starting point where every player begins with 10% markup. The results are demonstrated in figures 13.16 and 13.17. As usual, competition will reduce profit, this time down to a Nash equilibrium

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[1] Random access memory

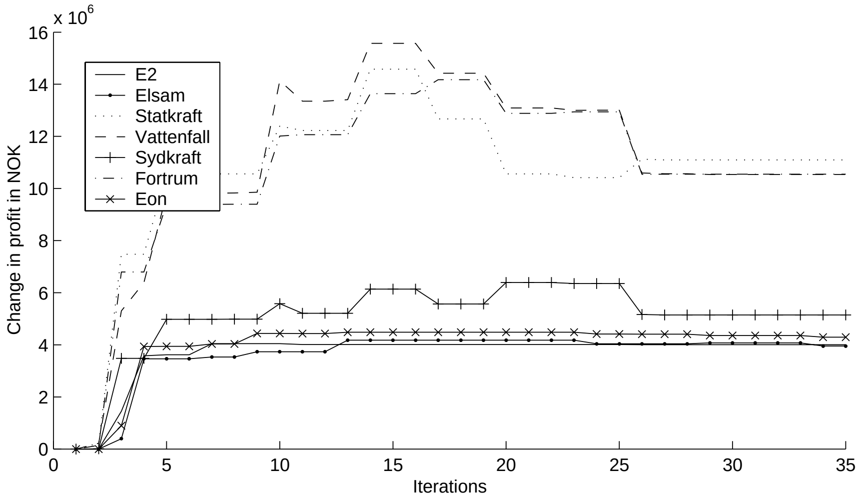

Figure 13.15: Profit change for weekly Nash equilibrium search

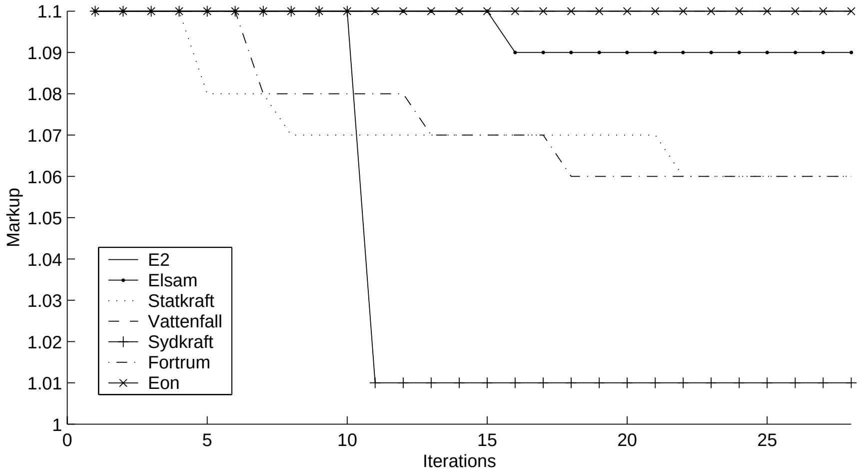

Figure 13.16: Whole week Nash equilibrium from 10% markup

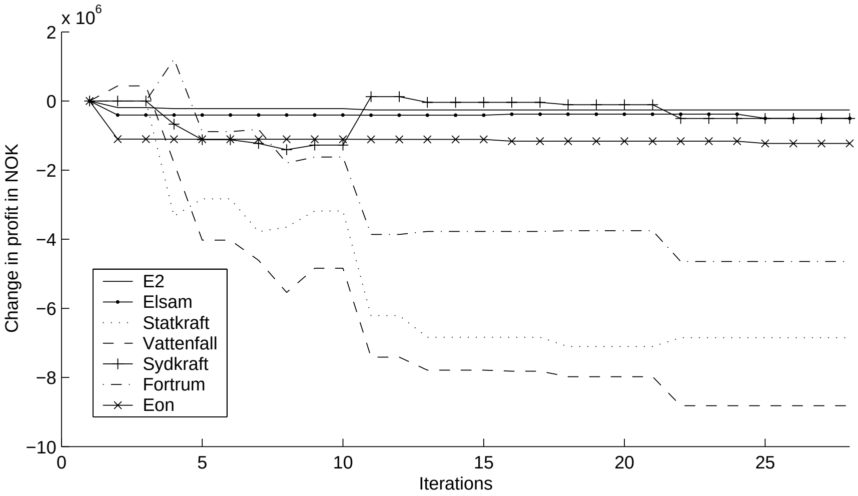

Figure 13.17: Dwindling profit

found very close to the equilibrium from the earlier search when coming from the opposite direction.

A search for Pareto optimality is illustrated in figure 13.18. The search maximized the combined profit of all players, starting at 0% markup. As expected, the solution is found where each player uses maximum markup.

Statkraft, Vattenfall, and Fortum are the only players to benefit to any extent from the Pareto optimal solution, compared to the Nash equilibria found in this section, as most of the other players were using maximum markup anyway. Therefore, the support of other players for any form of cooperation may be minimal.

13.5 Comparison to actual prices

In this section I will compare some of the prices found to the actual prices during the week from Monday to Sunday, February 10-16, 2003. Prices without markup, the Nash equilibrium found in the last section, the Pareto

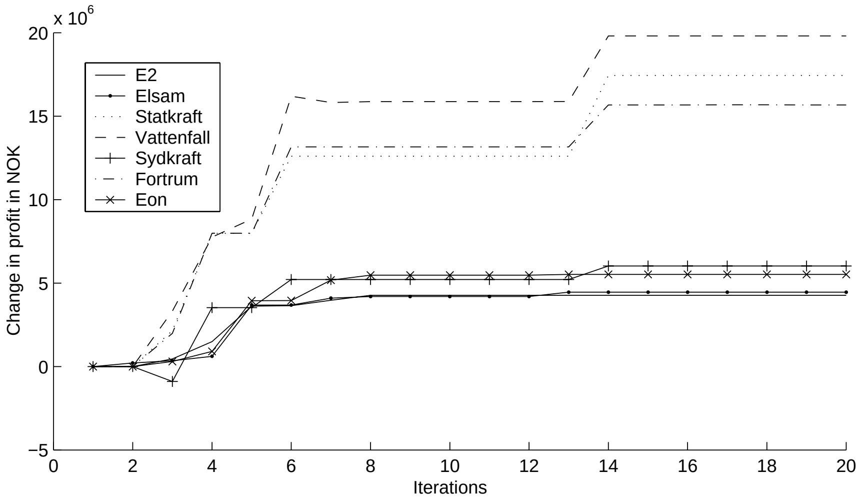

Figure 13.18: The merit of cooperation

optimal solution with 10% markup and the actual prices that week, are compared.

Figure 13.19 shows the prices in western Denmark for this period. As the Nash markup was 9% there is almost no difference between the Nash and Pareto solutions. However, the actual prices are far higher than any of the other modelled prices. There is, however, a correlation between the actual price and other prices during the working days, but the demand during the weekend seems to have been underrated. The actual price appears to be between NOK 100 and 200 above the modelled prices.

Figure 13.20 illustrates the prices in Sweden. Here there is a larger difference between the modelled prices and as in Denmark, the actual prices are far higher. There is also a correlation between the actual prices and the modelled prices during working days, but the weekend demand appears yet again to have been underrated.

Finally, figure 13.21 shows the prices in Germany. Although the actual prices are far closer to the modelled prices, especially during the night and at weekends, the price difference during peak demand is considerable.

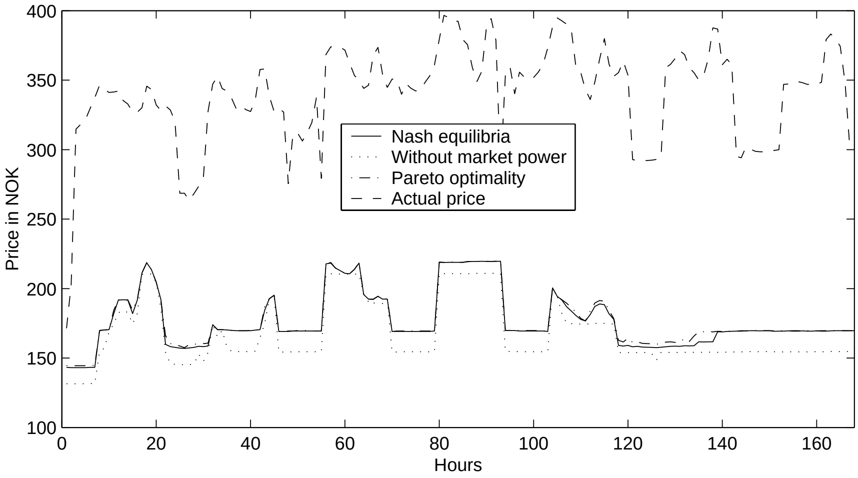

Figure 13.19: Prices in western Denmark

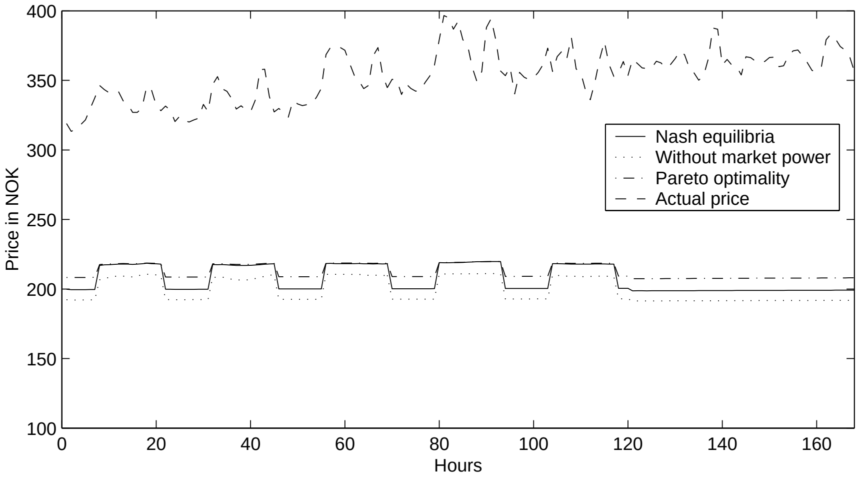

Figure 13.20: Prices in Sweden

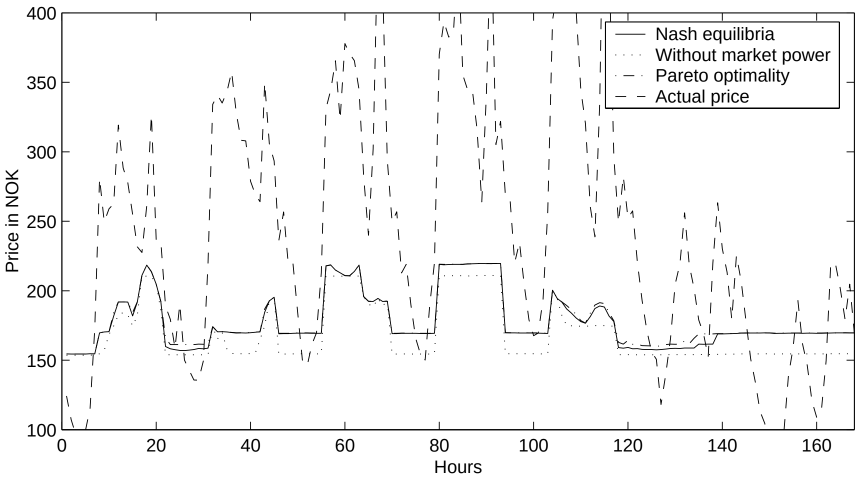

Figure 13.21: Prices in Germany

All three markets are characterized by the same shortcomings in the modelling, as opposed to the actual prices.

- There is too small price difference during the day and the night
- Prices are too flat during the weekend
- Prices are too low

It is worth taking into account that prices were considerably higher during this period in early 2003, than they had been in the previous years. This is demonstrated in figure 13.22 which shows the average daily prices from July 1999 to July 2003. Although it is clear that the model and data fail to simulate the actual price level during this exceptional time, it would have been more accurate had it been for February 2002 instead of 2003.

The model does not accurately reflect the actual prices for the period in question. The reasons could be:

- Demand was underestimated
- Changes in demand during the days were underestimated
- Actual unpredicted outages may not have been taken into consideration in the data

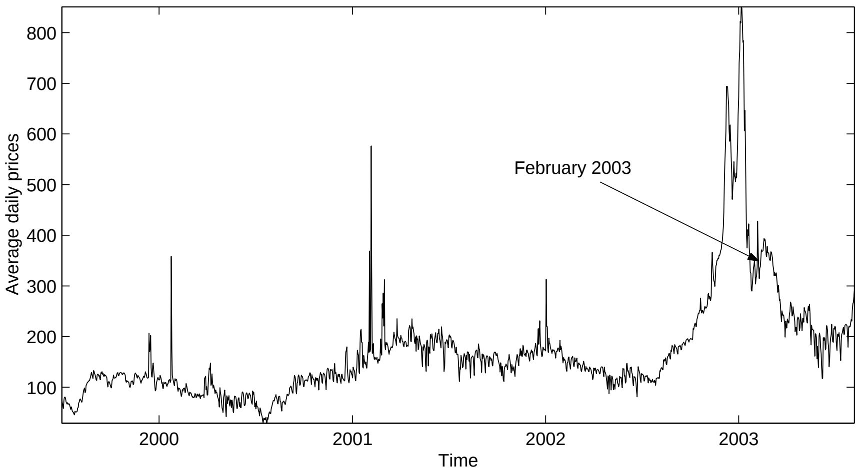

Figure 13.22: Average daily system price on the Nord Pool spot market

- The markup that players use is far greater than the 10% used in the models
- The production cost given in the data may be too low
- The water reservoir prospects given in the data may have been too optimistic
- Market power was being exercised on a considerably greater scale than expected

Unless a closer match between the model and actual prices can be made, using the model and the data to build real price strategies may prove futile. The data is, however, a platform, which should help in understanding the market and building models which may help either to detect market power or to use it. One must always take into consideration that prices were unusually high during February 2003 and models are usually built for 'normal' circumstances and thus do not handle 'extreme' situations well. The data and model might therefore have performed better in simulating actual prices at another time.

13.6 Searches and results

In this chapter, I have searched for Nash equilibria and Pareto optimal solutions. Although some were found, they must be taken with reservation as the application of this method to the real market may be quite difficult.

13.6.1 To be or not to be

The Nash equilibria found were usually unstable as pure strategy equilibria often became mixed strategy equilibria when the step size was decreased. Therefore, in a way they never existed but were only the result of an approximation of discreet strategies.

The definition of the only 'true' Nash equilibria has to be when no possible strategy of any player will increase that player's profit. And strategies between the discreet steps, must be considered possible strategies. Therefore, many of the pure strategy Nash equilibria found were not in reality Nash equilibria.

13.6.2 Incomplete information

To be able to find a Nash equilibrium, players must be able to select their optimal strategy. For the selection, a player must either know the exact demand and bids of other players or be able to determine his best strategy by stochastic or systematic search (trial and error).

The problem is that neither approach is easily accessible. The necessary information is not publicly available and guessing, based on the system price, volume traded, international transmission and ones own bids, will leave a lot of uncertainties.

Although, if partially accepted, the highest accepted bid would be at the market price, no information would be available on how large a part of it was accepted or the price and volume of the lowest unaccepted bid or second highest accepted bid. Had the highest accepted bid been fully accepted, of which there is no way of telling, information on neither the volume nor the price of that bid would be available.

This makes the findings in chapter 11 rather unhelpful, as they require the knowledge of not only other bids around the market price, but also their production cost, in order to select the optimal price strategy and to make the correct underbidding.

Regarding the stochastic or systematic search, for the detection of the optimal strategy, it requires the ability to change prices frequently in order to check the new strategies. However, this is not possible as "changes in market behavior that is not motivated by serious commercial or technical circumstances must not occur." Therefore, such a search would take some time, and during that time, different circumstances may have arisen on the market, such as different temperature, season etc. This may make the eventual comparison of strategies obsolete.

13.6.3 Unpredictability

To add to the difficulties, unpredictability plays a part in making the optimization of a price strategy more difficult as the market and market prices can be constantly shifting. The following factors will add to the variation of market prices:

- Wind power and winds
- Water reservoir levels, rain and temperature
- Temperature
- Outages of power plants and transmission lines
- Opening up of new installations or closing down of old ones
- Changes in other players' strategies

13.6.4 Enlightenment

If we assume that all the necessary information was available to a player, he would still have difficulties in deciding his optimal strategy. As demonstrated in section 13.2, a short term effort to increase profit may sometimes almost certainly result in a considerably lower market price with less profit for all players. Such a strategy would probably not be selected by a player possessing all information, including information on how other players will most likely respond. Can such a shortsighted strategy in that case be considered profitable, although it may be so for a very short period?

This takes us to the definition of Nash equilibrium. Should the Nash equilibrium be defined for only a short term profit or for a long term profit, taking into account the expected response of other players? Is a combination of Pareto and Nash more likely to be an ‘equilibrium’ than a basic Nash equilibrium?

13.6.5 Market power and Nash equilibria

To be able to find Nash equilibria, some information must be available. The information alone would be enough to decide whether market power was taking place, as any price above the production cost of the last unit produced is, according to definition, a result of market power.

Therefore, as it is not only difficult find Nash equilibria on the Nord Pool’s spot market, but also defining it, search for Nash equilibrium cannot be considered an effective tool for market power detection.

Part V

Conclusions

Chapter 14

Conclusions

14.1 Overview

In this thesis, I have described the Scandinavian electricity power market, the forming of Nord Pool and the characteristics of the market and electricity markets in general.

I have discussed some of the elements of the game theory that can be applied to the power market, in order to explain the behavior, strategies and options of the electricity producers, as well as discussing the different forms of competition and cooperation that can exist between them.

Furthermore, I have addressed some of the possible forms of market power, from changing prices or withholding production, to wrong predictions and blocking grid lines, and the possible benefits of each approach for different producers under different circumstances. I also discussed who will gain and who will lose by the use of market power and what can be done to detect it.

Finally I performed an extensive search for Nash equilibria and Pareto optimal solutions, which can both be clear indications of market power.

14.2 Results

14.2.1 Market power

There are quite a few ways to exercise market power and changing prices is only one of them.

Market power is when prices are higher than the actual production cost. Indeed, if production cost, production and demand is known, prices without the use of market power can easily be calculated. Any price above that price indicates that market power is being used, whether that price be a Nash equilibrium or not.

Market power also carries a disadvantage for its user and the main beneficiaries will often be competitors, who do not have to pay the price of less sales. Market power also carries the risk of disclosure, which may have serious consequences. Therefore, it is not certain that the exercise of market power is always justifiable for producers.

14.2.2 Nash equilibrium

The search for pure strategy Nash equilibria showed the weakness of that approach and the instability of the equilibria found. Pure strategy Nash equilibria disappear with different sets of strategies and other Nash equilibria may be formed.

14.2.3 Pareto optimality

With a very few players, mindless competition will hurt the players with low prices, to the customers' delight. Especially when the Nash equilibria are as unstable as mentioned above, finding a more favorable solution for all players, than any Nash equilibrium, would be fairly possible.

14.2.4 Parameters

Both Nash equilibrium and Pareto optimal solutions are greatly dependant on the parameters being used. In addition to the production cost and production quantity, is is necessary to know the maximum markup and whether all players are in fact using market power. Any deviation may result in considerably different solution.

As demonstrated in section 13.5, the modelled prices did not accurately reflect the actual prices for the period in question. While a more accurate simulation of the prices cannot be made, based on available data, searching for Nash equilibria will not give useful findings.

Wind, temperature, rain, outages etc., add to the instability of possible solutions.

14.2.5 Incomplete information

Given the difficulty involving finding a Nash equilibrium, when knowing every move of the other players, finding an equilibrium, not knowing anything except from own bids, prices on each market, international transmission and total sales, is far more difficult. A players cannot assume much about all the bids he must underbid to make more sales nor how much he can increase prices and not be replaced by other players. And for a player to know whether his own strategy is the optimal one, can be difficult when prices can only be changed at a slow rate and different circumstances may have arisen later, making the comparison obsolete.

14.3 Conclusions

My findings are that although applying elements of the game theory to the Scandinavian electricity power market may help us to understand the behavior and functions of the market, searching for Nash equilibria does not, with current information, contribute much to the detection of market power. Less ‘sophisticated’ approaches, as described in section 10.7, will probably produce more useful results.

14.4 Further studies

Further studies may include more stochastic approaches in finding optimal strategies for players, as the mean or average situation, may not necessarily yield the best solution.

Part VI

Appendices

Appendix A

Elspot areas and bidding information

A.1 ELSPOT AREAS AND BIDDING INFORMATION

1.1 Elspot areas are those areas, into which the Electricity Exchange Area is divided in order to remedy capacity constraints, if any, in the grid. The borders of the Norwegian elspot areas may vary. For the remaining of the Electricity Exchange Area the borders are firm.

1.2 The System Operators determine how the elspot areas are to be divided and the transmission capacity, i.e. the maximum power flow allowed between the elspot areas.

1.3 For Participants who bid in Norwegian elspot areas the System Operator in Norway may, in accordance with NVE's "Guidelines for the system operator", define a elspot area as a monopoly area if a producer or consumer in the relevant area are so dominant that normal market mechanisms do not work. On such occasions, Bids related to the relevant area are totaled with Bids related to the most suitable neighboring area so that the areas have a common price.

1.4 Every Thursday before 12:00 noon NPS shall inform the Participants of the price range within which Bidding may be made during the week to come; of the elspot areas for which separate Bidding are to be given; and of the definition of the elspot area borders. The price range is the upper and lower price for which Bidding may be made. The price range can be changed from day to day when required.

A.2 BIDDING FOR PURCHASE AND SALE

2.1 Bidding may only take place in areas where the relevant Participant undertakes production, consumption or is party to contracts relating to physical delivery or purchase.

2.2 Hourly Bid is the Participant's specification of purchase and sale per hour. In the hourly Bid the Participant shall submit a set of price/quantity specifications for each purchase and/or sale he wishes to make, divided into hours and elspot areas.

2.3 Block Bid is the Participant's specification of purchase and sale for an in advance determined number of hours. In the block Bid, the Participant shall submit average price and average volume per block. NPS determines which hours are to be included in each block.

2.4 Flexible hourly Bid is the Participant's specification of possible additional sales in the hour with the highest price, with received hourly and block Bids as the basis for calculation. The Participant specifies price limit and volume for a flexible hourly bid in a specific elspot area.

2.5 Bidding from Trading- and Clearing Representatives shall be specified for each Clearing Customer and for the Trading- and Clearing Representative's own Bidding.

2.6 The Participant shall use the Bidding to achieve energy balance in each elspot area. In order to control that this is done, NPS may require documentation for the Participant's basis for Bidding. This document is a translation and does not constitute a legally binding document 20

2.7 The Participant may submit hourly Bids, block Bids or flexible hourly Bids for one or several days within the period for which elspot areas have been determined. An hourly Bid and a flexible hourly Bid can be valid in one or several days. A block Bid is valid in one block only. New Bids may be made for periods for which a Bid has already been made, provided that 2.1 above is observed. It is the hourly Bid last received that counts.

2.8 By no later than 12:00 noon each day the Participant has to submit his Bidding relating to the next day.

2.9 Prices are to be quoted in a currency approved by NPS. The correct number of decimals to be quoted in each currency is determined by NPS. The Bidding may quote the number of MWh with up to one decimal. The Participants must make their Biddings for purchase and sale within the relevant price range. If NPS changes the price range in accordance with Article 1.4, The Participants must submit new Bidding for the remaining days of the week.

2.10 Bidding shall be made on NPS' standard bidding form and transmitted to NPS per electronic communication as specified by NPS. Fax may be used when approved by NPS. The Bidding form must provide complete information in order to be valid. Invalid or faulty Bidding will be rejected. In case of rejection, the price report received by the Participant from NPS will declare that no contract is concluded.

2.11 NPS may in exceptional and isolated situations claim that the Participants make Biddings for several following 24-hour periods. NPS shall in such situations give notice of the situation to the Participants at the latest one week in advance and simultaneously inform of how many 24 hour periods which must be included in the Bidding.

A.3 PRICE SETTING

3.1 The price/quantity specifications of the Bids will be regarded as points on a bidding curve created by drawing straight lines between the points.

3.2 The block Bid is granted the tender if the criteria below are met. A block Bid (sell) is granted a tender if the average price for the hours is similar to or higher than bidden price. A block Bid (buy) will be granted a tender if the average price for the hours is similar to or below bidden price. In addition, the submitted volume must be fulfilled. The selection is based on the following criteria: 1. The difference between submitted price and average area price. This means that the block bid which has the largest difference between submitted price and average area price will be excluded first. This document is a translation and does not constitute a legally binding document 21 2. Energy, which means volume multiplied with the number of hours in the block. If the difference between submitted price and area price is equal, then the block bid or the combination of the block bids that gives the largest turnover will be given priority. 3. Time of storing. If two block bids or combinations of block bids are similar, then the bid which is first stored in NPS price setting database will be given priority.

3.3 A flexible hourly Bid may be granted the tender if the price- and volume criteria are met. NPS may decide that a flexible hour Bidding shall not be granted the tender if it alters the status for tenders of the block Bids. NPS' priorities of flexible hourly Bids shall be based on the following criteria: 1. Price; being the difference between the price of the flexible hourly Bid and the area price. 2. The time of the storing in the database. Item 3.2 (3) applies correspondingly.

3.4 Based upon Biddings received NPS first calculates a system price. The system price is the price in those elspot areas that at the relevant time are included in the system price calculation. The system price calculation is done by aggregating all Bids in one buy curve and one sell curve without considering potential capacity constraints between the relevant areas. The point of intersection between the two curves establishes the system price.

3.5 If the power flow between two or more elspot areas exceeds the transmission capacity, two or more area prices will be calculated.

3.6 If situations occur where a point of intersection between the buy curve and the sell curve is not achieved, NPS may reduce Bids on a pro rata basis until an intersection point is achieved.

3.7 Any imbalance between total purchase and total sale caused by the rounding off of quantity for each Participant when accurately calculating the price will be distributed within each elspot area (system price or area price).

3.8 All prices are calculated in NOK and are converted to other currencies.

A.4 REPORTS OF PURCHASE AND SALE

4.1 When the price has been calculated NPS informs the Participant of its calculated purchase/sale in a price report which shall be submitted to the Participant before 13.30 hours the day preceding the day for which the price is given. The price report specifies the price and quantity for each elspot area for which the Participant has bidden. Price reports to the Trading- and Clearing Representatives are specified for each Clearing Customer and for the Trading- and Clearing Representative's own Trading. If transmission of the price report is delayed, notice shall be given.

4.2 If the Participant wants to claim an error in NPS' handling of a Bid, NPS shall be notified before 14:00 hours on the same day. The Trading- and Clearing Representatives claim errors on behalf of Clearing Customers. The Participant shall if relevant, receive a new price report before 14:30 hours. If transmission of the price report is delayed, the Participant is granted 30 minutes to submit notice of error, calculated from when the price report is transmitted from NPS, and correspondingly NPS has one hour to resend a corrected price report, if relevant. Upon expiry of the notice period the price report transmitted will be regarded as a contractual obligation for the quantities specified in the price report.

4.3 In situations described in 2.11, NPS will, if needed, determine separate rules for price reports and deadlines for submitting notice of errors.

Appendix B

Matlab codes

In the following section, a few of the most important types of the matlab algorithms I wrote, can be found.

B.1 Price calculations

```
function [C,m,pris]=nordpoolshort(M,KAP,z)
% M is matrix made of 12 vectors where the first 6 give the price
% of the supply function and the latter 6 the demand function for
% each of the 6 markets.
% KAP(i,j) gives the maximum transmission capacities from market
% i to market j.
% z=1000; %The starting number of unit transfer between markets.

he=0; %Counter
zz=5; %The factor of how z is decreased
log1=0; %Varible which decides when to stop the main loop

[nn,antakt]=size(M);
%Defines length and breadth of the main information matrix M

antakt=antakt/2; %How many markets there are
```

```
C=zeros(antakt,antakt);
%C(i,j) is the current export from market i to market j

pd(1:antakt)=0; %Netto import to a market

for k=1:antakt %Initial price calculation before exports

  [pkk, mk] = min( abs(M(:,k)-M(:,antakt+k)) );
  %Finds where the difference between supply and demand is
  %least for each market

  m(k)=mk;
  %Marks the current position of the current price in each market

  pris(k)= M(m(k),antakt+k);
  %Finds price in beginning before exports and imports

end

changed=[1:antakt];
% Defines which markets need to be calculated

while (log1 ~=1)
  %The main loop, will end when log1 becomes 1

  he=he+1; %Counter
  tpd=pd-z; %Moves forward or backward when export or import

  if length(changed)==2
    % After a normal transmission only the 2 relevant markets
    % needs recalculations.

    overf(:,changed(1))=1;
    overf(changed(2),:)=1;
    % Allows calculations of export from markets which exported in last
    % iteration and import for markets which imported in last iteration
    % Other calculations are unecessary as they have already been made

    % The following lines find new prices for each market when receiving
    % import or export. They only checks for new price in the area from
    % last known price and up to + or - z (the transfer unit)
    % in case of exporting or importing
```

```
    r1=changed(2);
     % r1 is the market which received import last iteration

    [pkkn1, mkn1(r1)] = min( abs(M(-z+m(r1):m(r1),r1)-
    M(pd(r1)+m(r1):pd(r1)+m(r1)+z,antakt+r1)) );
    % New position for maret r1 when receiving import z
    prisn1(r1)= M(pd(r1)+m(r1)+mkn1(r1)-1,antakt+r1);
    % New for price for market r1 when receiving import z

    r2=changed(1); % r2 is the market which received export last iteration

    [pkkn2, mkn2(r2)] = min( abs(M(m(r2):m(r2)+z,r2)-
    M(tpd(r2)+m(r2):tpd(r2)+m(r2)+z,antakt+r2)) );
    % New position for market r2 when exporting z
    prisn2(r2)= M(tpd(r2)+m(r2) +mkn2(r2)-1,antakt+r2);
    % New price for market r2 when exporting z units

  else
    % When z has been changed, or in the beginning, export and import
    % for all markets must be calculated

    overf=ones(antakt,antakt); %Makes all calculations necessary

    for r1=changed
      % This loop does the same as in above, except all markets are checked
      % for export and import, instead of only 1 for export and 1 for import.

      [pkkn1, mkn1(r1)] = min( abs(M(-z+m(r1):m(r1),r1)
      -M(pd(r1)+m(r1):pd(r1)+m(r1)+z,antakt+r1)) );

      prisn1(r1)= M(pd(r1)+m(r1)+mkn1(r1)-1,antakt+r1);

      r2=r1;

      [pkkn2, mkn2(r2)] = min( abs(M(m(r2):m(r2)+z,r2)-
      M(tpd(r2)+m(r2):tpd(r2)+m(r2)+z,antakt+r2)) );

      prisn2(r2)= M(tpd(r2)+m(r2) +mkn2(r2)-1,antakt+r2);

    end
  end

  overf = and(overf,(KAP >= C+z));
```

```
% overf(i,j) is 1 when legal transmission is possible from market i to j.
% This marks all legal, when KAP >= C+z and necessary when overf<>0
% calculations

[oi,oj]=find(overf); % Vectors with the position of legal transmissions

if(oi) % If any legal transmission

  for i=1:length(oi)

    r1=oj(i);
    r2=oi(i);

    if pris(r1)>pris(r2) % Export is possible if the receiving country
      % has higher price and there is enough capacity

      overf(r2,r1)=(abs(prisn1(r1)-prisn2(r2))<= pris(r1)-pris(r2));
      % But only if the price difference between markets becomes less

    else

      overf(r2,r1)=0; %If the price in exporting market is higher,
      % export is illegal

    end
  end
end

if find(overf)  %Checks wether there is any legal move

  [s1, s2] = sort(pris); %s2 sorts the markets after the
  % current price, the market with the highest price is last

  im=antakt; %Varibles used to find best import
  ex=1;  % and export

  while ~overf(:,s2(im))
      % Finds the most expensive market which can receive import

    im=im-1; % Checks for next market

  end
```

```
    j=s2(im); %j is that market

    while ~overf(s2(ex),j)
        % Finds the cheapest market which can export to market j

      ex=ex+1;  % Checks for next market
    end

    i=s2(ex); % i is that market

    C(i,j) = C(i,j) + z;
    % Energy of volume z is transferred from market i to market j

    pd(j)=pd(j)+z;  % Netto import for market j is increased

    pd(i)=pd(i)-z; % Netto import for market i is decreased

    mkn1(i)=z-mkn2(i)+2; % Position of import changes

    m(i)=m(i)+mkn2(i)-1; % New positions of price

    prisn1(i)=pris(i); % Old price become new export price

    pris(i)= prisn2(i); % and new price is old export price.

    mkn2(j)=z-mkn1(j)+2; % Position of export changes

    m(j)=m(j)+mkn1(j)-1-z; % and new position found

    prisn2(j)=pris(j); % Old price becomes new import price

    pris(j)= prisn1(j); % Old import price becomes new price.

    changed=[i,j];
    % The market that have changes. What is necessary to calculate are
    % new import price for j and export price for i other information are
    % reused.

  else % Well, if there was no legal export or import

    if z>1

      z=ceil(z/zz); % we will decrease the amount transferred
```

```
      changed=[1:antakt]; % and must calculate all markets with new z

    else

      log1=1; % unless z is already 1 and then we will end the main loop

    end

    % The following lines net out the transmission, if transmission from
    % i to j and from j to i, the lesser transmission becomes 0 and the
    % greater transmission the difference

    CC=C';
    [i,j]=find(and(C>CC,CC));

    if i

      for k=1:length(i)
        C(i(k),j(k))=C(i(k),j(k))-C(j(k),i(k));
        C(j(k),i(k))=0;

      end
    end

  end

end % The end of the main loop
```

B.2 Data preperation

```
function [S,D, mpt,mpro]= hentmp3(uge,dag,time,tol)
% Function which takes the number of week, day and hour
% as well as the minimum unit.

tic

load eltra % Loads Etra's data including demand which is the demand data,
% timi, which is the time index for the supply data, and supplymp which
% which is the supply data, and supplier, which is the supplier index
% in the supply data.

q3=5000; %Highest price

m=6; %How many markets

vektor=find(and(timi(:,1)==uge, and(timi(:,2)==dag, timi(:,3)==time)));
sup1=supplymp(vektor,:);
% Finds the supply elements for the correct date


vektor=find(and(demand(:,1)==uge, and(demand(:,2)==dag,
demand(:,3)==time))); dem1=demand(vektor,4:end);
% Finds the demand elements for the correct date

%%%% Calculates new demand
vektor=[2:2:m*2];
dvol=dem1(:,vektor-1); % The volume
dpris=dem1(:,vektor); % and the price are found
mx=floor(max(max(dvol))/tol); %How many units in vector

nydem1=zeros(mx,m); % The new demand later

for i=1:m
    % This loops interpolates the demand for each of the markets
    % between the data points given by Eltra

    [mest,hvar]=max(dvol(:,i));
    dvec=interp1(dvol(1:hvar,i),dpris(1:hvar,i),[tol:tol:mest]');
    nydem1(1:length(dvec),i)=dvec;
```

```
end

%%%%%%% Calculates new supply
n=size(sup1); supplier=n(2)/2; offers=n(1); vektor=[2:2:n(2)];
 svol=sup1(:,vektor-1); spris=sup1(:,vektor);

supply=[];
market=[]; %Which market
producer=[]; %Number of producer
pt=[]; %Producers team
counter=0; ;

%%% The following loops find each supplier, and interpolates his supply for
%%% all the markets as well as recording his ownership
for i=1:supplier
    [mest,hvar]=max(svol(:,i));
    if mest>0

        svec=interp1q(svol(1:hvar,i),spris(1:hvar,i),[tol:tol:mest]');
        ls=length(svec);
        supply(counter+1:counter+ls,1)=svec;
        producer(counter+1:counter+ls,1)=ones(ls,1)*i;
        counter=counter+ls;
     end
end

pt=team(producer); % Records faction ownership for each element in the supply
market=landn(producer); % Records on which markets each faction operates

%Sorts markets
msup=ones(mx,m)*q3;

%%% The following loop adds all the supply functions for all the producers
%%% togehter for each market, sorts it, and keeps record of the ownership
%%% and type of each plant.

for i=1:m
    vektor=find(market==i);
    l=length(vektor);
    s=supply(vektor);
    [q,si]=sort(s);
    msup(1:l,i)=s(si);
    mpro(1:l,i)=producer(vektor(si),:);
```

```
    mpt(1:l,i)=pt(vektor(si),:);
end

[q,qq]=max(msup); q=max(qq)-1;

D=nydem1(1:q,:)*tol; % The demand matrix
S=msup(1:q,:)*tol; % The supply matrix
```

B.3 Iterative search for Nash equilibrium

```
% This program randomly selects market, finds the best solution for
% that market and keeps that solution.
% This is version is with sepperate markup for subsidiaries in other markets

tic clear
tol=1; %Minimum unit in MWh
[M,D,pt,pd]= hentmp3(7,1,1,tol); %Gets data for week, day, hour and with
% minimum unit. M is supply, D is Demand, pt and pd are the ownership and
% power plant type of the supply.

init1 % Gets few text strings for the later plotting
toc tic
z=1000/tol; % Starting transfer between markets
KAP=KAP/tol; % The allowable maximium transfer between markets
ww=[1:0.001:1.1]; %Steps and scope of price changing
load eltra teammarket; %Load data about on which markets teams operate

[stm1 stm2]=size(teammarket);

M=[M;[5000*tol*ones(z,antakt)]];
D=[D;[zeros(z,antakt)]]; %Extends M to avert fails in Sweden
pt=[pt;[zeros(z,antakt)]];

MM=M; kk=0; toc tic kkk=0;

r=0;
other=0; %Which market is not to be tested.
lm=length(M);

[temp, lam]=max(M); %Actual length of each market

player=[2, 4, 8,10,9, 7, 6]; lp=length(player);
other=zeros(lp,1);
tvekt=[];
vektor=ones(stm2,lp);

tind=zeros(lm,lp,antakt); tindl=zeros(lp,antakt);

for i=1:lp
  for j=1:antakt
```

```
    t=find(pt(1:lam(j),j)==player(i));
    tindl(i,j)=length(t);
    if(tindl(i,j))
      tind(1:tindl(i,j),i,j)=t;
    end
  end

end

fpt=pt; oldprice=zeros(lp,antakt); price=ones(1,antakt);

%Fast
information(1,2,stm2)=0; income(1,lp)=0; cost(1,lp)=0;

while and(kkk<300,sum(other)<lp);

  r=floor(rand*lp)+1;
  while other(r);
    r=floor(rand*lp)+1;

  end
  toc
  tic
  mm=player(r);
  for tm=1:stm2
    am=teammarket(mm,tm) %Active market
    if am>0
      if oldprice(r,am)==price(end,am)
        other(r)=1;
      else
        kk=0;
        kkk=kkk+1

        if kkk==1
          www=1;
        else
          www=ww;
        end
        for w=www;

          kk=kk+1;
          fvekt=find(fpt(1:lam(am),am)==mm);
          MM(fvekt,am)=M(tind(1:tindl(r,am),r,am),am)*w;
```

```
    [MM(1:lam(am),am),f]=sort(MM(1:lam(am),am));
    fpt(1:lam(am),am)=fpt(f,am);
    %end

    information(kk,:,tm)=[mm w];

    [C,m(kk,:),pris(kk,:)]=nordpoolshort([MM,D],KAP,z);

    %for i=1:lp

    for i=r
      for j=teammarket(player(i),
      1:length(find(teammarket(player(i),:))))

        salg=find(fpt(1:m(kk,j),j)==player(i));
        lsalg(kk,i,j)=length(salg);
        mincome(kk,i,j)=lsalg(kk,i,j)*pris(kk,j);
        mcost(kk,i,j)=sum(M(tind(1:lsalg(kk,i,j),i,j),j));

      end
      income(kk,i)=sum(mincome(kk,i,:));
      cost(kk,i)=sum(mcost(kk,i,:));
    end

  end

  profit=income-cost;

 [bb,best]=sort(profit(:,r));

 vektor(tm,r)=information(best(end),2,tm)

  fvekt=find(fpt(1:lam(am),am)==mm);
  MM(fvekt,am)=M(tind(1:tindl(r,am),r,am),am)*vektor(tm,r);
  [MM(1:lam(am),am),f]=sort(MM(1:lam(am),am));
  fpt(1:lam(am),am)=fpt(f,am);

  kk=best(end);

  for i=1:lp
    for j=teammarket(player(i),
    1:length(find(teammarket(player(i),:))))
```

```
            salg=find(fpt(1:m(kk,j),j)==player(i));
            lsalg(kk,i,j)=length(salg);
            mincome(kk,i,j)=lsalg(kk,i,j)*pris(kk,j);
            mcost(kk,i,j)=sum(M(tind(1:lsalg(kk,i,j),i,j),j));

          end
          income(kk,i)=sum(mincome(kk,i,:));
          cost(kk,i)=sum(mcost(kk,i,:));
        end

        profit=income-cost;

        price(kkk,:)=pris(best(end),:);

        vek(kkk,:,: )=vektor(:,:)';
        opt(kkk,:)=profit(best(end),:);

        if opt(kkk,r)==opt(max(1,kkk-tm),r)
        else
          other=zeros(lp,1);
          oldprice(r,am)=price(kkk,am);
        end
        other(r)=1;
      end
    end
  end
end

figure hold for i=1:lp
  plot(vek(:,i,1),texti3(i,1:3))
end legend(firmanavn(player,:),0) xlabel('Iterations');
 ylabel('Markup');
 v=axis;
 v(4)=w;
 v(2)=kkk;
 axis(v);

figure hold for i=1:lp
  plot(opt(:,i)-opt(1,i),texti3(i,1:3))
end legend(firmanavn(player,:),0) xlabel('Iterations');
ylabel('Change in profit in NOK');
 v=axis;
 v(2)=kkk;
```

```
axis(v);

figure hold for i=1:antakt
  plot(price(:,i),texti2(i,1:3))
end
 legend(marketnames,0)
 xlabel('Iterations');
 ylabel('Prices at each market in NOK');
 v=axis;
 v(2)=kkk;
axis(v);
```

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