Algorithms for Electronic Power Markets

BY

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Abstract

In this thesis we focus resource allocation problems and electronic markets in particular. The main application area of ours is electricity markets. We present a number of algorithms and include practical experience.

There is an ongoing restructuring of power markets in Europe and elsewhere, this implies that an industry that previously has been viewed as a natural monopoly becomes exposed to competition. In the thesis we move a step further suggesting that end users should take active part in the trade on power markets such as (i) day-ahead markets and (ii) markets handling close to real-time balancing of power grids. Our ideas and results can be utilised (a) to increase the efficiency of these markets and (b) to handle strained situations when power systems operate at their limits. For this we utilise information and communication technology available today and develop electronic market mechanisms designed for large numbers of participants typically distributed over a power grid.

The papers of the thesis cover resource allocation with separable objective functions, a market mechanism that accepts actors with discontinuous demand, and mechanisms that allow actors to express combinatorial dependencies between traded commodities on multi-commodity markets. Further we present results from field tests and simulations.

Keywords: multi-commodity markets, electronic markets, computational markets, equilibrium markets, resource allocation, power markets, computational complexity

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Jakob and Anna
The work behind this thesis has to a large extent been carried out within EnerSearch AB.

EnerSearch is an industrial research and development consortium in the energy sphere. The company aims at initiating and carrying out research projects of interest for the industry. The main interest is in business models and in utilisation of information and communication technology within the energy business.
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<th>Description</th>
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<tr>
<td>B2B</td>
<td>Business to Business</td>
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<td>B2C</td>
<td>Business to Consumer</td>
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<tr>
<td>C2C</td>
<td>Consumer to Consumer</td>
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<td>CHP</td>
<td>Combined Heat Power</td>
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<tr>
<td>CRISP</td>
<td>distributed intelligence in CRitical Infrastructures for Sustainable Power (project acronym)</td>
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<td>DG</td>
<td>Distributed Generation, that is power generation close to end users in MV and LV grids.</td>
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<td>HV</td>
<td>High Voltage (power grid)</td>
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<td>ICT</td>
<td>Information and Communication Technology</td>
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<td>ILS</td>
<td>Intelligent Load Shedding</td>
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<td>LV</td>
<td>Low Voltage (power grid)</td>
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<td>MV</td>
<td>Middle Voltage (power grid)</td>
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<td>Photo Voltaic (power generation)</td>
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<td>SDM</td>
<td>Supply – Demand Matching</td>
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<td>TSO</td>
<td>Transmission System Operator</td>
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Chapter 1

Introduction

Resource allocation problems are present in our everyday life. They may range from the world of family problems and e.g. how to share sweets among children, or how to use the money left when it is all too long to payment day, to global issues such as sharing of scarce water resources between needs, peoples and nations. Resource allocation problems give raise to numerous conflicts between children and adults, and they are all too often the cause of wars. Put in another way, they are an essential and challenging part of everyday life, for all of us.

Hence, resource allocation problems are challenging in many ways, and they are subject to research and discussions within many disciplines. The interest is not only formulated in spheres of economy and politics, but in many other fields, all the way to the formulation of faith and theology. The Bible is full of texts on problems related to resource allocation; one example is the critique from the prophets such as Amos (Amos 8:4–7), another the words of Jesus (e.g. The Gospel of Luke 12:13–34). Two examples from our time are Dorothee Sölle [42] and Leonardo Boff [6].

Different tools are used to handle resource allocation, depending on the context. An instrument we often consider as a “natural” resource allocation instrument is the market. Numerous resource allocation problems are handled by markets.

The focus of this thesis is on computational aspects of resource allocation and (electronic) markets. We develop and suggest a number of algorithms both for resource allocation in general and for electronic markets in particular. The work started in late 1998 and was performed within a number of projects, the latest one is the ongoing CRISP project.

The main motivation for the work is the development of concepts ap-
plicable to future electricity markets. Since the liberalisation of electricity markets started it has become more and more obvious that we need new and better tools for matching of supply and demand. Electronic markets involving end users may become such a tool.

1.1 Resource Allocation

A bowl of rice on the table, together with some other dishes. People around the table, maybe friends and family. We are well acquainted with the situation. We want to share the meal such that hopefully none leaves the table hungry and disappointed.

It is there all the time and everywhere, the problem of how to share available resources. The resource might be scarce, or it might be abundant, but the task of sharing is there. It may concern almost any area of life; sometimes the problem of how to share is easy, sometimes it gives raise to conflicts.

We use different metrics when it comes to how to solve resource allocation problems. Sometimes when the resource is scarce, the strongest takes what he wants and everyone else has to be content with the leftovers. A perhaps more civilised and accepted way to handle resource allocation is the notion of a market. The basic idea of a market is that the balance between supply and demand gives an equilibrium price. Assuming that the commodity of interest is a good, and it is abundant on a market with low demand, the price is relatively low. If supply decreases and/or demand increases, the equilibrium price increases.

When we have a metric governing the resource allocation that can be expressed as a mathematical maximisation or minimisation problem, we can use computers to aid the resource allocation. Sometimes we could guarantee that the computed solution is optimal, sometimes the computational complexity is to hard for this. In such cases we can only strive for optimal solutions to special categories of problem instances and have to accept approximative solutions when it comes to more general categories.

Resource allocation problems could be formulated in many ways. The formulation of the model affects the computational complexity of the problems. Input functions may have different shape, and they may express different kinds of dependencies. Restricting ourselves to cases with a single

\footnote{In principle, we could think of commodities that the consumer(s) do not like or are indifferent to. In that cases we could discuss the commodity as a bad of a neutral. In this thesis the commodities on the market are assumed to goods.}
The problem has a number of application areas including load distribution, production planning, computer scheduling, portfolio selection, and apportionment. Further it appears as subproblems of more complex problems [21].

A way to differentiate problems is to determine whether the resource is continuous or discrete. Further, we may decide whether the problem is separable, convex (concave), a minimax problem or a maximin problem, etc. Such properties are essential as they can be utilised in algorithm design.

An aspect that sometimes is interesting when evaluating if an algorithm is a good choice is whether it relies hard on the number of agents that are to share the resource(s). (Here an agent represents e.g. a process, a person, or whoever has interest in the resource allocation.) Another related aspect is whether it is applicable to distributed resource allocation problems or not. A distributed problem is when the information needed is spread over some world, e.g. over a power grid. Some information is available in the control room, while other information is in the hands of end users (consumers and small scale producers).

When the number of agents is relatively small and information is centrally available at low communicational cost, standard continuous optimisation algorithms as presented e.g. in the textbook Numerical Recipes [35] can be a good choice. Some approaches to problems with large numbers of agents and/or a distributed setting are presented e.g. in the thesis of Ygge [47].

1.2 Electronic Markets

Electronic markets or e-markets are nothing but ordinary markets. When we specify that a market is electronic we give a technical description of the market, saying that in one way or another computers and computer networks such as the Internet are used by the market. Well known examples are auction sites such as eBay [16] and electronic book shops such as Amazon.com [1]. Less known is that the use of e-markets started as a way of sharing scarce computational resources, i.e. the notion of a market was suggested to be used as a means of allocating a scarce resource and this resource was the computational power itself. Today electronic markets are
extensively used in other less well known areas, particularly in different business-to-business (B2B) relations.

From a research viewpoint there are aspects of e-markets that fall into both business and economics, as well as computer science. In this thesis we use basic economic theory in an effort to develop algorithms for different markets that are interesting from e.g. the viewpoint of power markets.

Simplified, we could say that research in economics is a study of real world phenomena rendering simplified models focusing on different essentials of interactions in society. Hopefully we are able to understand these interactions better through this modelling. Such an understanding may in turn influence the interactions that was studied. For a deeper understanding of microeconomic theory, there are a number of textbooks available, e.g. [20, 26, 28, 43].

The main computer science interest is in how to utilise this theory to construct mechanisms for electronic markets.

1.3 Structure

The thesis is structured with an introductory part followed by attached articles/papers. In the introduction we have a chapter giving an introduction to the main application area, electric power systems. Chapter 3 contains a motivation for the use of electronic markets in the field and a discussion on alternatives.

After this we give a short introduction to some concepts from economics that are useful when reading the papers, Chapter 4. The last two chapters of the introduction give a description of contributions and a few concluding remarks.
Chapter 2

Main Application Area

Electricity plays an increasingly important role in modern society. Not only is demand for electrical power increasing, but demand for reliable power supply and power quality increases too. This demand is a challenge for power suppliers and power markets of today and tomorrow.

Interestingly enough, the effects of deregulation of power markets partly goes in a contradictory direction. An experience from a number of markets is that power companies on liberalised markets are reluctant to hold marginal capacity for extreme demand situations and other situations that threaten system stability and power delivery. Whether this is due to competition leading to lower margins or a reevaluation of responsibility for system stability is out of our scope. However, concepts in the thesis influence how the market can handle the situations.

More interesting is that in this situation the industry might reevaluate an old and well established “truth”, saying that consumption (as well as small scale local production) has to be handled with fixed price, long term contracts. As a consequence of this traditional attitude the balancing of supply and demand has to be handled entirely by the large actors on supply side, which naturally limits the possibilities to handle balancing efficiently.

There are a number of possible ways to influence power consumption e.g. in a strained situation; they range from utilities and authorities informing the public of the risk for shortage and outages, over actions involving prepared load reduction schemes to novel approaches such as electronic power markets. Handling of these situations when system load moves towards its upper limits is a major motivation for electronic power markets but the gain is not limited to these situations.
Note: The problem we focus is different from the “unit commitment problem” as applied to today’s power markets, e.g. Hobbs et al [19]. The unit commitment problem is focusing the supply side task of picking the most efficient power production units.

2.1 A Short History of Electricity in Sweden

Production and usage of electrical power started to play an active role in the Swedish society in the 1890s. Industry that could benefit from usage of electricity localised factories where the possibilities for hydro-based power production were good. The localisation of factories to such areas was nothing new, since hydro power had been used for long in mills of different kinds. What was new was the usage of electricity as power carrier with its flexibility and advantages.

This first production of electrical power was a strictly local phenomenon. The technique for distribution and transmission over longer distances was not yet developed. In the 1930s the transmission grid of Sweden was built. It could be mentioned as a matter of curiosity that even though the transmission grid was not built until then, the first Swedish experience of international exchange of electrical power dates back to 1915. Since long, the power grids of the Nordic countries are integrated to a large extent [27].

As the first production was tightly coupled to industrial usage of the power, the ownership was in the hands of these industrial interests. But, already in the first decade of the 20th century the first pure power companies in Sweden were founded. Furthermore, municipalities and the government took a growing interest in the sector. As the close connection between production and consumption vanished and was replaced by pure power companies the idea of a natural monopoly was established; that is, power companies where sole responsible for power delivery in entire towns and regions.

From the beginning of the era of electrification of Sweden until now hydro power has played a dominant role in power production. Being one of the few nations with high availability of hydro power (and on top of this nuclear power), Sweden has a high consumption of electrical power. For example, Sweden is one of few countries with a high percentage of electrical heating in residential buildings. (To use fossil fuel\(^1\) to generate

\(^1\)Even though the main power production in Sweden is based on hydro power and
electricity for heating purposes, with energy losses in the order of 60–70% is clearly a misuse of energy.)

Production and delivery of electricity was considered a natural monopoly for long. During recent years the monopoly situation has changed and now the monopoly is reduced to transmission and distribution, turning production and delivery of electricity into activities exposed to competition.

In Sweden the market was deregulated in the mid 1990s. The Swedish deregulation came a few years after the Norwegian, and was followed by a EU-wide deregulation that is not yet fully carried out. With the deregulation we moved from vertically integrated utilities to separation of production from distribution (even though a production company and a distribution company in Sweden may have a common owner). The Nordic power exchange NordPool — the world's first international commodity exchange for electrical power — organises trade in both physical (Elspot) and financial power contracts including clearing services to Nordic participants [29].

2.2 Current Market in Sweden

The NordPool market covers the area of the five Nordic transmission system operators Statnett (Norway), Svenska Kraftnät (Sweden), Fingrid (Finland), and Eltra and Elkraft System (Denmark). We are mainly interested in the day-ahead market, Figure 2.1.

Sweden and Finland have a common adjustment market, Elbas [17], to handle changes in consumption and sales when the day-ahead market has closed. Elbas provides continuous trade up to an hour prior to delivery. On this market hourly contracts are traded. The market perspective of Elbas is not handled here, but it could be viewed as a kind of after-market to the day-ahead market.

Today the Swedish balancing of the grid as elsewhere, involves a few large actors only. The responsible party is Svenska Kraftnät, the Swedish transmission system operator (TSO). The real-time balancing is often viewed as a two level spinning reserve; the primary reserve is handled fully automated and handles real-time fluctuations. The secondary one (in this work denoted balancing service) handles larger trends and it is organised

nuclear power, marginal consumption is often covered by (imported) fossil fuel power plants.
as a simple market, with bids on positive and negative adjustment of power. The active parties submit bids per hour, and the time frame from trade to effectuation is in the order of a few minutes, price fluctuations on this market can be substantially higher than prices on the day-ahead market, Figure 2.2.

Deregulation of markets in the Nordic countries and in Europe introduces new problems and challenges. One of them is how to handle fluctuations in supply and demand, and particularly how to handle peak
hour consumption.

2.3 Challenges of Today and Tomorrow

There are a number of interesting and challenging problems related to power markets of today and tomorrow, and we mention some of them here:

- The basic characteristics of electricity markets, that supply has to meet demand at every instant has to be met by the control systems, market based or not,

- production, and even more consumption, of electricity varies a lot due to a number of factors, such as season, weekday or weekend, time of day, and weather conditions,

- even though there has been a lot of political discussions on how to reduce power consumption in countries like Sweden, it is steadily increasing,

- increasing demand ought to give an increase in production, but on the contrary, as a result of deregulation and political decisions we have experienced a reduction in active production capacity as well as in reserve capacity needed to handle extreme demand situations,

- the demand for reliable supply of power is increasing as modern society becomes increasingly vulnerable to power shortages and outages, and

- there are problems inherently related to the structure and limitations of current markets and their dynamics.

All these issues are essential and interrelated. Some market related aspects are highlighted in this thesis.

2.3.1 Market Constraints

Electricity markets differ substantially from most other markets. Unlike most input to production processes electricity cannot be efficiently stored to increase flexibility of production and consumption. This can be expressed by noting that even though the commodities traded on electricity
markets are energy volumes\(^2\) (often bound to a time period), the commodity that is delivered is power, the first order derivative of the traded good.

The character of electricity puts specific demands on any control system for an electricity grid, whether purely control oriented or market based. At the same time we note that the more information a control system has on production and consumption etc. the better the possibilities to handle the situation.

2.3.2 Variations in Supply and Demand

The consumption of electricity has substantial seasonal variations. In countries such as Sweden, consumption during winter is higher than consumption in summer, as electricity is used for heating. In other countries it is the other way around as electricity is more extensively used for cooling.

On top of these seasonal fluctuations we have fluctuations over the day — the consumption at 3 AM in the morning when most of us are asleep is substantially lower than it is at 9 AM when we are at work.

As electricity cannot be efficiently stored and demand has to be met instantly, production and transmission/distribution has to be dimensioned for a demand that is considerably higher than the average.

Furthermore, there are supply side variations too. Leaving the introduction and withdrawal of production capacity out of scope we have the water supply of hydro power that varies from one year to another. In shorter perspectives we have the fluctuations in wind based production, and in the future some European countries might have the corresponding problems related to photo voltaic (PV) production.

Power systems have to cope with all these constraints and fluctuations, and in particular in liberalised power markets this has to be done in an economically efficient way.

2.3.3 Increasing Demand and Decreasing Reserve Capacity

It is easy to understand that the trend of the last years with a decrease in reserve capacity cannot continue. We have faced a continuing increase in

\(^2\) An exception is trade related to real-time balancing of power systems. In this case the traded commodity is power.
demand for electrical power. At the same time market liberalisation, political decisions on the structure of electricity production, etc. has resulted in a decrease in production capacity. In particular, spare capacity needed for to cover demand during critical days/hours has been withdrawn.

We do not intend to enter a political discussion on the issues related to the mismatch between developments in demand and in supply, but we agree with those who claim that this obviously is or may become a severe problem.

2.3.4 Reliability

Our dependence upon electrical power supply has increased tremendously during the last decades. Our society has become vulnerable and it is essential to increase power reliability. Reliable power supply is likely to become a product of increasing market value in the near future.

2.3.5 Static Electricity Markets

Current market structures are far from optimal. They give no incitements to end users to utilise their potentials to change their consumption/production patterns in a way that is beneficial from a systems viewpoint. Such incitements could be an essential part of the development of tomorrow’s power systems.

2.4 Market Perspectives of Electricity Markets

In micro-economic theory there is a differentiation between market time frames, a basic distinction could be done between the “short run” and the “long run”. This differentiation reflects what flexibility actors have in the short run and in the long run [28, p. 346]. Take a producer, in the short run he is limited to his current status when it comes to production facilities and input factors, as we extend the time frame his flexibility increases. On consumption side we have the corresponding differences between time scales. That is, all market actors have different kinds of flexibility and limitations depending on time scales.

As in any industry, the limitations and flexibility of actors are essential when it comes to electricity. In a relatively long run perspective production and distribution facilities are constructed, as well as consumers change their ways of relying on electricity and alternatives. On the other
hand we have the real-time and close to real-time situation where electricity markets have a harder demand for a match between supply and demand than other industries.

In the following sections we give a short presentation of a few time perspectives of the electrical industry, and their market implications.

2.5 The Long Market Perspectives

In the time frames of decades and years new power lines and other facilities are constructed, and old ones are closed down. Power markets face changes in regulations, such as the major change that the industry has faced recently in many countries and currently is facing in other; the movement from a “utility structured” electricity market towards a market with open competition between suppliers on different levels.

In the still long time frames of years down to months mainly bilateral contracts are settled between actors on the market, hedging risks and creating stability.

These perspectives are not in focus of the work presented in this thesis even though the movement towards electronic markets and end user participation on these markets belongs here.

The time frames that we have in mind span from day-ahead markets down to markets that clear minutes ahead of real-time. Longer time frame markets are affected indirectly with actors moving from long term static contracts to dynamic markets. The need for hedging may be handled using financial instruments, as in other sectors.

2.6 Day-Ahead Markets

As the name indicates a day-ahead market is a marketplace where the traded commodities are to be delivered the following day. The aim of the market is to handle fluctuations in demand and supply that could be foreseen within the perspective of the market, e.g. fluctuations in demand due to season, weather, day-of-week, time-of-day, etc, but also fluctuations on production side due to production units being down, etc.
The structure of day-ahead power markets differs in details from marketplace to marketplace. In principle delivery of energy is traded on a hourly or half-hourly basis, i.e. the traded commodity is a combination of volume and delivery time. Hence, the number of commodities traded simultaneously is typically 24 or 48.

As soon as more than one commodity is traded at a time, the question of how to express dependencies between the commodities arises. On markets such as dynamic electricity markets, particularly when small scale actors are acting on the markets, these dependencies could be significant.

Even though participants may have various types of dependencies and constraints between time slots, there is no — or very weak — support for expression of such dependencies on today’s power markets.

Actors on day-ahead power markets of today are large producers and suppliers, i.e. consumption side and small scale production, as well as local distributors, are not directly represented.

2.7 Grid Balancing

The more accurate the outcome of the day-ahead market is, the smaller are the deviations in production and consumption between market outcome and reality. At the same time, it is not possible to achieve a perfect match on the market such that there is no need for trade on more fine-grained markets, and in the end to make final adjustments of production in real-time.

As mentioned in Section 2.2, Svenska Kraftnät is responsible for the
balance in the national transmission grid. The regulation of production to meet fluctuations in consumption and to compensate for differences between estimated consumption and actual consumption could be divided into a primary and a secondary regulation.

The primary, real-time regulation, i.e. small adjustments of production to meet fluctuations in consumption, is in Sweden mainly performed by regulation of hydro plants. This regulation is performed automatically and is outside the market perspectives that we consider in this thesis.

On a secondary regulation level the approach of today’s is market oriented. A number of large actors take part in the balance responsibility. For each hour they submit bids reflecting their ability to increase and decrease their production (or consumption). The bids are ordered according to the price, Figure 2.3. Continuously, a few minutes ahead of real-time bidders are contacted to adjust up or down. Finally, all actors that take part in the regulation are paid according to the highest price of the hour.

![Figure 2.3: All bids on regulating power (both up and down) are ordered in a staircase shaped function, such that the grid operator can pick the best offer when taking action.](image)

2.8 Load Shedding

Even though the power systems of developed countries such as Sweden are very reliable, there are emergency situations where the system moves towards instability and in the end towards an outage. In 2003 we had three such major events that all ended up in power outages, one in the US, one at the border of Italy and Switzerland, and the third was an outage in southern Sweden and Denmark [4, 18].
An instrument in the hands of the grid operator that is essential when a power system moves towards instability is “the red button”, the ability to shut down power delivery to parts of the grid to restore stability in the system. Today, most load shedding systems act on the middle voltage (MV) level, cutting delivery on 10–20 kV power lines. The approach is rather rough and insensitive, and protection of critical load has to be built into static schemes for what areas to pick. An example is that the operator tries to avoid areas with a lot of elevators [8]. It seems obvious that load relief can be obtained in a much more sensitive and smart way.

To keep record on load that is available for instant shut down or reduction (in one way or another) we denote intelligent load shedding (ILS). Intelligent load shedding is not treated in any of the papers within the thesis, but it is part of ongoing work within the CRISP project. One interesting approach is to use a market mechanism for ILS.

A note: The expression intelligent load shedding is said to have its background in a system blackout situation. It was a utility top level manager that introduced the term. To his knowledge a load shedding system was installed to take care of severe, rare disturbances, such that system wide blackout should be avoided. This system had obviously failed and the manager stated that “we need a more intelligent load shedding system” [8].

2.9 Potentials and Challenges

In all the three fields of day-ahead power markets, balancing services, and load shedding we do see potentials to develop new interesting market concepts. Some suggestions are presented in this thesis.

The challenges differ from area to area, day-ahead markets and similar are cleared well ahead of real-time and the time constraints are not that hard, on the other hand there are interesting challenges when it comes to preference profiles and bidding opportunities on multi-commodity markets, particularly interdependencies between traded commodities (time periods).

In the other end we have the completely novel field of intelligent load shedding and how to apply market concepts to this area. In this case there is only one commodity traded, load available for instant shut-down or reduction. Here, the time constraints are in focus, as load shedding is a means for fast action to avoid that the system goes towards an unstable state. The time available to take proper action depends on the
disturbance. Voltage and frequency instability give a few seconds to a minute. If this time frame can be utilised to restore system stability by load reduction this is a gain for all parties.

In between we have close to real-time balancing of supply and demand in the grid, the secondary spinning reserve that is activated with a few minutes of lead time. Here utilisation of end user flexibility and electronic markets could well be interesting. In this case the market could be organised in different ways, from a single commodity market to a multi-commodity market with a small number of commodities traded simultaneously. The challenges resemble the ones that we find in the other two market perspectives, hence time constraints are an issue, as well as bidding opportunities.
Chapter 3

Two-Sided Electronic Power Markets and Alternatives

There are a number of motivations for the development of electronic power markets. We identify two major motivations in (i) the potential to increase the economical efficiency of the markets, and (ii) handling of critical situations when it is hard to match supply and demand. Further we find (iii) the concept of market based load shedding highly interesting.

This chapter is devoted to a comparison of three alternative methods to achieve what we pinpoint in the first paragraph. Two of them are market based, one is not. The first one is two-sided electronic markets. The second one is a market based, bottom-up method too, and we denote it price-reactive optimisation. The third method is a top-down approach that stems from the old monopolistic power utility days that we denote peak-load shaving.

Even though only two of the three methods are market related we define the time-frames of the actions in terms of markets. First we have the perspective of a day-ahead power market, i.e. actions are planned hours ahead of real-time, and the time resolution is in the order of an hour (alternatively half an hour). Second we have the perspective of grid balancing close to real-time (the secondary spinning reserve), with a market horizon of an hour and with a few minutes between decisions and effec-tuation. Third is the emergency situation when intelligent load shedding can be an option to restore system stability (voltage and frequency).

With this we get a two-dimensional scene and we want to evaluate the advantages and disadvantages of the thee methods. The scene is visualised
in Table 3.1.

Table 3.1: *A two dimensional description of the scene. The time frames of day-ahead and shorter might all be handled using a number of techniques. In this chapter we compare the three methods with respect to all three time-frames.*

| Day-ahead Balancing Load market service shedding |
|---------------------------------|-----------------|
| Peak load shaving               |                 |
| Price-reactive consumers and DG | — ? —           |
| Full electronic markets         |                 |

Throughout this chapter we mainly discuss end users in terms of consumers, hopefully this gives a straightforward description and it should be easy to translate what is said to the perspective of DG.

### 3.1 Description of the Balancing Methods

#### 3.1.1 Full Two-Sided Electronic Markets

In the long run, both sides influence market prices on competitive markets. In the short run markets such as current day-ahead power markets could be viewed as one-sided markets (see next section). Other markets are two-sided, that is both supply side and demand side are active in the price establishment.

A two-sided electronic power market (the main concept of this thesis) is a market with full participation in the price establishment from end user side.

#### 3.1.2 Price-Reactive Optimisation

Without major changes in the market structures we cannot achieve full end user participation on power markets. An alternative that can be applied to current (day-ahead) market structures is price reactive optimisation.

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1 A competitive market is a market where all agents act competitively, Chapter 4.
3.1 Description of the Balancing Methods

A consumer with hourly metering paying according to a dynamic tariff that is correlated with the prices on the day-ahead power market can optimise his consumption pattern to minimise his cost. In the same way, an end user with controllable production capacity who is payed a corresponding dynamic price may optimise the utilisation of his production capacity, Figure 3.1. Local controllable production could for example be micro-CHP (combined heat power) units used for building heating and electricity production or small hydro plants.

![Figure 3.1: Left: The potentials of price-reactive systems can be illustrated with the help of this rather extreme market outcome, a price dip followed by a price peak (we assume that it is related to a corresponding demand variation). Right: The obvious response of price-reactive actors is to move consumption away from the peak price period, and to move production into it.](image)

Figure 3.1: Left: The potentials of price-reactive systems can be illustrated with the help of this rather extreme market outcome, a price dip followed by a price peak (we assume that it is related to a corresponding demand variation). Right: The obvious response of price-reactive actors is to move consumption away from the peak price period, and to move production into it.

Price-reactive optimisation is a concept that fits with markets that could be defined as one sided posted price markets, i.e. markets where either supply side or demand side sets the price and the other side adapts its behaviour to this price.

3.1.3 Peak-Load Shaving

Peak load shaving, Figure 3.2, is a concept that has been in use during the last decades. For example, the Swedish utility company Sydkraft was highly involved in development of such schemes during the late 1980s [25, 31, 32].

As seen in Figure 3.2 peak-load shaving enforces a shift in consumption. Automated systems utilising simple signaling to trigger immediate load reduction always give a delay in consumption. (In principle more complex information could give local control systems the opportunity to schedule their reactions, moving consumption ahead of the period with load reduction as well as delaying it.)
In a residential setting target loads typically are tap-water boilers that are shut off for a predefined period and heating/cooling that is reduced.

3.2 Communications and Computations

All systems for supply – demand matching etc. involving end users need supporting systems to handle communications, computations and load control (effectuation).

3.2.1 Communications

Three essential aspects on communications are (i) information volume, (ii) communication speed, and (iii) need for bi-directional communications. The information volume that is communicated depends on method as well as time frame/market perspective:

- Regardless of time frame, peak-load shaving is based on a minimum of information. In systems designed for automated peak-load shaving a simple signal triggers a predefined behaviour in the control equipment installed at end user premises.

- It is obvious that price-reactive optimisation needs information on market prices. This is more information than in the previous, and the information is more complex, but it is not more than a price vector.

- Two-sided electronic markets utilise modern ICT (information and communication technology) capabilities more than the other two.
Depending on market setup the information volumes exchanged could be rather high, in particular on a day-ahead market with opportunities to express combinatorial bids. Markets can be designed to reduce close to real-time communications. This is an essential issue when it comes to load shedding.

ILS relies on high communication speed (as well as reliable communications). The time frames of SDM give that communication speed is not that critical.

Two-sided electronic markets are based on bi-directional communications. For peak-load shaving and price-reactive optimisation it suffices with one-way communications, even broadcasting is sufficient as there is no need for personalised information, Figure 3.3 and 3.4.

**Figure 3.3:** Peak-load shaving could rely on rather limited communicational resources. As action schemes are predefined, it is sufficient to be able to send a simple signal when load reduction is needed. No personalised information is needed.

**Figure 3.4:** Electronic markets are based on modern ICT. There is a need for both personalised information exchange, and for an ability to transmit larger information volumes.

### 3.2.2 Computations

Both in some central marketplace/control room and at end user premises all three techniques depend on computational capacity (and control equipment).

Peak-load shaving can be either automated or manual on control room side. At end user side it relies on control equipment taking proper action when receiving a signal.
Price-reactive optimisation in SDM settings has higher demands on computations, as it involves optimisation that sometimes turns out to be rather sophisticated [24]. The one and only task on price posting side is to publish prices.

A central task of agents representing actors on two-sided electronic power markets is bid construction. The complexity of the task varies with market protocol, but in general the demand on computational capacity is at least as high as for price-reactive optimisation. The task on market side is collection of bids, possibly involving aggregation, and calculation of market prices. The complexity of this task depends highly on the market protocol.

3.2.3 End User Internals

An end user node of an SDM/ILS system has an internal structure, with its communications and computations. Peak-load shaving is based on simple signal – response schemes (predefined actions are taken when receiving a signal). In both market based approaches the internal structure of an end user system might be rather complex. It may even be organised as a miniature market with comfort zones and appliances as actors represented by software agents [5, 12, 13, 24, 48, 50].

3.3 Advantages and Disadvantages

We make a limited comparison of the three methods on a high level, the comparison is directed towards SDM (with ILS left out):

- **Peak-load shaving**
  - An advantage of peak-load shaving is that it has been proven to be useful [25, 31, 32].
  - The cost of peak-load shaving systems is moderate.
  - The big disadvantage is that peak-load shaving is a top-down control system that does not fit to well into a liberalised power market [8].

- **Price-reactive optimisation**
  - Price-reactive optimisation is applicable to current day-ahead power markets for any end user under contracts with hourly prices.
3.4 Conclusions

+ The main advantage is illustrated in Figure 3.1. Price-reactive optimisation moves demand away from peak price periods, and moves supply into the same periods. Hence the strain on such periods is released.

- The main disadvantage can be explained using the same figure. To really influence the system the number of price reactive end users should be large. There is a lack of information on the price elasticity\(^2\) of the optimising actors that may cause problems when their influence becomes substantial. Market prices of today are based upon estimations of production and consumption, bottlenecks in transmission, etc. Price-reactive actors may well wreck the stability of these prices.

If price-reactive actors should become other than marginal, the relation between it and the system (including establishment of prices) is an area of further research.

- Two-sided electronic markets

+ The main advantage is that two-sided electronic markets are a true way to involve consumption and DG on dynamic power markets. This gives that (i) the dynamics of end-users find their way to the market, and (ii) we get a market outcome based on more knowledge compared to the outcome of current markets.

- No disadvantages except that the concept is a novel approach that involves restructuring of the market.

3.4 Conclusions

Peak-load shaving is a simple and straight-forward technique that did fit well into the old structure of power markets with vertically integrated power utilities. It is harder to see how it could fit into liberalised power markets.

Both market based methods fit well into liberalised power markets. Among the two we identify two major differences: Price-reactive optimisation is applicable to current market structures, two-sided electronic markets are not. On the other hand, the price elasticity of end users is

\(^2\)Price elasticity: the effect a price change has on supply and demand.
what we want to bring forward with both concepts; price-reactive optimisation does not reveal any information on this elasticity — and this can become a problem as depicted in Figure 3.1, two-sided electronic markets do not suffer of this drawback.

We believe that peak-load shaving does not comply with liberalised markets. Price-reactive optimisation has its major drawbacks, but may well be a step in the direction of two-sided electronic markets.

Two-sided electronic markets is a step further compared to deregulated markets as we know them today. With two-sided electronic markets we move from dynamic power markets focused on wholesale to full involvement of end users, DG actors as well as consumers.
Chapter 4

Market Theory

This chapter is a short introduction to some microeconomic theory with relevance for the thesis. We briefly cover optimisation and equilibrium, demand and supply, utility, competition, monopoly and oligopoly, and auctions.

For a deeper understanding of microeconomic theory, there are a number of textbooks available, e.g. [20, 26, 28, 43]. The inspiration for this chapter has mainly been the book by Varian [43].

4.1 Economic Efficiency

When discussing market outcome we need efficiency measures. In everyday life there are different measures typically used by different actors and they are typically focused on the objectives of the actor himself, and not so much on the total market outcome.

During a coffee break at work we may discuss market situations in terms of how expensive everything has become or maybe in terms of bargains we made the other day. The prevalent perspective is the consumer’s perspective.

In the board room of the company the perspective is different. An essential goal for the company is profit maximisation. The task of profit maximisation could be more or less complex and naturally involves both acting as a buyer on several markets and as a seller on other markets. Here it suffices to conclude that the measures we use when acting as sellers are different from the ones we use as consumers, even though they all are about utilisation of available resources in an efficient way.
The criterion for economic efficiency is value (and value is subjective). A change that increases value is an efficient change and another change that decreases value is inefficient.

A standard efficiency measure used in economics is \textit{Pareto efficiency}, or whether a mechanism is \textit{Pareto optimal} or not.

\textbf{Definition 4.1} A way to make somebody better off without making anybody worse off is a \textit{Pareto improvement} \cite{43}.

The notion of Pareto improvements gives the definition of Pareto optimality:

\textbf{Definition 4.2} A market outcome is said to be \textit{Pareto optimal} if no Pareto improvements are possible.

This is one way to define economic efficiency, and it is used in this thesis. The search for value can be discussed in terms of utility maximisation and profit maximisation. The search for value is the driving force of market economies.

\section{Auctions}

Auctions are one of the oldest forms of markets, and they are popular. Consumer-oriented auctions could even partly be viewed as entertainment, auctions on the countryside in Sweden certainly are. Other consumer-oriented auctions that attract growing interest are the Internet based auctions where we could buy or sell almost anything.

We note that “auction” is a word that covers much more than these kinds of auctions. In principle any market mechanism using a bidding process (iterative or one-shot bidding) is denoted “auction”.

Auctions are an instrument that is heavily utilised within business to business relations, both selling and buying auctions are common.

\subsection{Single Commodity Auctions}

The basic auction concept is an auction where someone has a single item for sale and there are a number of potential buyers (bidders). In an \textit{English auction} the auctioneer start at the reservation price of the seller, i.e. the lowest price the seller accepts. Bidders offer higher prices until there is
no one prepared to increase the bid, the item is awarded to the highest bidder at highest bid price.

Other bidding rules are the Dutch auction that essentially works the other way around. The auctioneer starts at a high price and gradually lowers the price until someone is willing to buy the item.

Further we have sealed bid highest price auction. This auction is theoretically identical to the Dutch auction. When any of the two auction rules are used the strategies of bidders depend not only on their own valuation, but also on expectations on other bidders’ valuations.

A last bidding rule that is of theoretical interest is the Vickrey auction. It is a sealed bid auction and the highest bidder is awarded the good, but at the second highest price. The idea is that this promotes that bidders enter their true valuations, and it can be proven that this is an optimal bidding strategy.

 Needless to say, auctions work as well the other way around, with a single buyer, a number of sellers bidding, and the lowest price bidder awarded.

Two questions are of special interest when it comes to construction and evaluation of auction mechanisms. Formulated from the perspective of selling auctions they are:

- **Profit maximisation.** Does the auction design yield the highest expected outcome for the auctioneer?

- **Pareto optimality.** Does the person with highest valuation get the item?

English auctions as well as Vickrey auctions achieves Pareto optimal outcomes. Dutch auctions and sealed bid highest price auctions does not have this property as the outcome depends on expectations on other bidders’ preferences.

We do not go into profit maximisation here, we just note that under certain conditions all four mechanisms have the same expected outcome. The conditions are that (i) bidders are risk neutral and that (ii) their valuations of the traded commodity are independent (“private value”). This is expressed in the revenue equivalence theorem, and described in any introductory text book in microeconomics.
4.2.2 Combinatorial Auctions

When the auctioneer has more than one commodity for sale the simplest thing to do is to arrange a number of consecutive or parallel auctions, one for each commodity. Often this is not optimal, neither for the auctioneer nor for the bidders, since a bidder’s valuation might depend not only on the price of the item, but also on prices of other items.

Two simple examples: (i) On a flight ticket auction I want to buy a round trip to London. The problem is that there are only one-way tickets sold. Hence I take a risk buying one of the tickets, not knowing if I will get both of them at a price not higher than my valuation. (ii) There are two cars for sale, they are identical except that one red and one blue. I have no preference when it comes to the colour, I am only interested in getting one of the cars at best possible price. My dilemma is that I cannot know if the first car or the second one will turn out to be the best buy.

The first example is an example of complementary goods, and the second one is an example of substitutes. An obvious solution to the problem is to allow the bidder to bid on bundles of goods, as well as enter bids on alternatives. Continuing the examples this would give me the opportunity to bid on a bundle consisting of the two flight tickets that I want for my London trip, and I would be able to express what I am prepared to pay for any of the two cars. With this we get a combinatorial auction, and the drawback is that computing the winning combination (assuming that it exists) is generally hard.

Since the combinatorial auction is a highly valuable instrument, it has attracted a lot of interest from the computer science community. There are two possible paths, either to allow all bids and not to guarantee that the solution of the winner determination is optimal, or to restrict the set of accepted bundles in such a way that an optimal solution (under the restriction) can be guaranteed.

Auctions are only one basic market concept. We now move to the more general concept of equilibrium markets.

4.3 Equilibrium Markets

On a high level of abstraction, when acting on different markets we do so to move from some state to another one, and we can assume that we prefer the state that we try to reach to the one we left. Expressed in a simple way, when possible we try to choose things that we want rather
than things we do not want. This is naturally viewed as an optimisation process.

The optimisation is based on our preferences. The preferences of all actors on a market are the basis for market prices.

A market is in equilibrium when the set of prices (one for each commodity) is such that supply meets demand. That is, when prices are such that the excess demand of all actors sums to zero for each commodity.

The actors’ preferences may be expressed in different ways. This is typically regulated by market protocols. A market may even restrict the possibilities to express preferences, e.g. to hold the computational complexity of a multi-commodity market at a practical level.

Basically we have two main approaches in the search for a market equilibrium: (i) price based and (ii) resource based. That is, in the price based approach the question is: “Given that the price of a pen is SEK 10, how many do you want to buy (sell)?” A resource based approach is to ask “at what price would you buy (sell) five pens?”

The question why I want to buy four or five pens given that the price is SEK 10 is not of interest as input to a market mechanism, it just needs the volume if it is to determine a market price.

4.3.1 Price Based Methods

Input Functions

We start with a market where we trade a single commodity for money. That is, a market with two parameters: (i) what is traded on the market and (ii) money. In the following we will use a simplification and denote this a single commodity market taking the money part for granted.

To isolate and focus a single commodity is a simplification. Our demand for different goods depends on a number of factors including prices and availability not only of the commodity itself but of alternatives and complements too. Still the simplification is useful; it makes market analysis as well as market computations relatively simple (compared to a situation where we want to look at a more realistic and complex picture).

When it comes to the construction of market mechanisms, we gave a motivation in the discussion on combinatorial auctions, Section 4.2.2. To continue the example of a London trip, we are less interested in the individual prices of flight, hotel rooms, theatre tickets, etc. and more interested in the total cost of a weekend in London, as well as total costs of alternative trips. In this example the fixed bundles with flight tickets,
hotels, and maybe entertainment, offered by travel agencies might be an interesting alternative. Fixed bundles might be less attractive on e.g. a power market.

The demand of a single actor on a market as well as the aggregate demand on the market could be expressed as a function of price, c.f. Figure 4.1. The aggregate demand is simply the sum of individual demands. The same holds on supply side, c.f. Figure 4.2.

All actors on a market with a price based approach have to be able to produce a demand (supply) function, explicit or implicit, since demand (supply) as a function of price is the format used on the market to express what they are willing buy (sell).

With this input we have two sets of functions, one expressing the intentions of the buyers on the market, one expressing the intentions of the sellers. We realise that if we view supply as negative demand (or the other way around, demand as negative supply) and sum we get the excess demand on the market as a function of price, Figure 4.3.

**Continuous and Decreasing Demand**

People are not always fully rational, but even though there might be exceptions we could assume that when the price of a commodity is increasing (everything else held constant) the demand for the commodity is non-increasing. In the same way we could assume that supply under the same condition is non-decreasing.
Due to e.g. limitations the price sensitivity on supply or demand side might be low, even zero, but it would be irrational if a higher price on a commodity would give an increase in demand. (Our assumptions might not hold e.g. when it comes to speculation on a stock market, but this is out of scope.)

Another classical assumption is that demand (supply) is continuous, see Figure 4.4. This assumption is essential as there might not exist an equilibrium price on a market where it does not hold. Hence a market protocol could demand that input functions are continuous.

This could be problematic since actors might well have non-continuous demand. The risk an actor with non-continuous demand takes submitting a continuous demand (supply) function typically has to be handled outside the market (e.g. within some adjusting after-market). How to handle non-continuous demand on single commodity markets is discussed in [9] (Paper Two of this thesis).
Market Prices and Allocations

As said previously, a market is in equilibrium when prices are such that supply meets demand for all commodities traded on the market.

On a single commodity market with decreasing (increasing) and continuous demand (supply), we could determine the market price starting with an initial guess. We could then determine the aggregate supply and demand on the market at this price. If the aggregated demand is higher than the aggregated supply, our next guess will be higher, and if the demand is lower than the supply, our next guess will be lower. We go on until we find a price where supply meets demand, the price cross, Figure 4.5.

A corresponding process can be modelled based on a single function expressing the excess demand of the market as a function of price, Figure 4.6.

Figure 4.5: With demand decreasing in price and supply increasing in price we can search for an equilibrium price, \( p^* \), such that demand equals supply. For prices lower than \( p^* \) demand exceeds supply, and for prices higher than \( p^* \) supply exceeds demand.

Figure 4.6: Supply may be expressed as negative demand. As in Figure 4.5, with demand decreasing in price we can search for an equilibrium price, \( p^* \), such that the excess demand equals zero. For prices lower than \( p^* \) excess demand is positive, and for prices higher than \( p^* \) excess demand is negative.

When a market mechanism is used to determine equilibrium prices on a multi-commodity market the problem becomes significantly harder compared to the single-commodity case. This is so since the space of possible outcomes is much larger. In the single-commodity case we want to determine the price of a single commodity neglecting dependencies between the demand for this commodity and demand for other commodities (as well as
supply side dependencies). In the multi-commodity case we take (at least some of) these dependencies into account when trying to establish a set of prices such that demand equals supply for each of the traded commodities. In the single commodity case the space of possible market prices is one-dimensional (we want to determine a single price), on a market where two commodities are traded the corresponding space is two-dimensional (we want to determine two prices taking dependencies into account), on a three commodity market the space is three-dimensional, and so on. In the general case when bidders are allowed to express any correlations between commodities, determination of equilibrium prices on a multi-commodity market is too hard to be practical. Approaches suggested in the literature are based on traditional continuous optimisation as well as on integer programming. Our basic approach is to limit the set of permitted bundles, i.e. what dependencies an actor could express, such that the computations become feasible. Two articles [10, 7] presented in this thesis are devoted to mechanisms designed for multi-commodity markets, Paper Four and Paper Five of the thesis.

4.3.2 Resource Based Methods

Input Functions

If the functions of Figure 4.5 and 4.6 are strictly monotonous, we could invert the function and the result is expressing price as a function of resource. That is, the inverse demand function expresses the price an actor or the actors on a market is prepared to pay for a marginal amount of the resource, and correspondingly the inverse supply function expresses at what price suppliers are prepared to increase supply with a marginal amount.

The inverse demand function or the *price function*, is proportional to the first order derivative of the *utility function*, a function that is basically a preference ordering (given two consumption bundles with different utility, the one with higher utility is preferred to the other one). The utility function can be used for a mathematical description of preferences. The function is interesting since in some settings it is more natural to construct a utility function based on the need for a resource than to construct a demand function. If normalised it can be used efficiently in the determination of market prices.

The condition for the relation between the inverse demand and the utility is that the utility function is *quasi concave*. 

Quasi-Concave Utility

The notion of a quasi-concave function might not be fully intuitive. A concave function (Figure 4.7) is quasi-concave, but the opposite might not hold. A relatively simple explanation of quasi-concavity is given in Sydsaeter and Hammond, Mathematics for Economic Analysis [41, pp.642]. The following is mainly inspired by that explanation:

Figure 4.7: The left function is concave and the right function is convex.

Definition 4.3 Let $f(x)$ be a function defined over a convex set $S$ in $\mathbb{R}^n$, and $a \in \mathbb{R}$. Define:

$$P_a = \{x \in S : f(x) \geq a\}$$

then $P_a$ is a subset of $S$ that is called an upper level set for $f$.

In economics the border of such an upper level set, where $f(x) = a$ of a utility function is known as an indifference curve, Figure 4.8. According to the metrics, two consumption bundles on the same indifference curve are equally good to the actor.

Quasi-concavity is given by:

Definition 4.4 A function $f(x)$, defined over a convex set $S$ in $\mathbb{R}^n$ is quasi-concave if the upper level set $P_a = \{x \in S : f(x) \geq a\}$ is convex $\forall a$.

As said, concave functions are quasi-concave, and in a number of settings e.g. related to electricity consumption, concave utility is natural. On the other hand there are situations where utility turns out not even to be quasi-concave.
4.4 Competition and Equilibrium

![Figure 4.8: An indifference curve is constituted of all consumption bundles resulting in an equal utility. In this two-dimensional example we have that for each indifference curve $U(r_1, r_2) = a$ for some $a$. Further the set that is defined by $U(r_1, r_2) \geq a$ is convex, hence the utility function $U$ is quasi-concave.](image)

**Market Prices and Allocations**

The utility function of an actor gives a value to allocations of the commodity (commodities) traded on the market. Given that the function is quasi-concave, the first order derivative of the function is proportional to the price he is prepared to pay for a small additional amount of the resource.

Correspondingly the first order derivative of the aggregate utility can be used to determine market prices.

### 4.4 Competition and Equilibrium

Ideally no actor (or small group of common interest) on a market is large enough to be able to control market prices with his behaviour. A participant that does not speculate on the effects of his behaviour on the market acts *competitive*. Another way to denote such an actor is to say that he acts *price taker*.

When actors on a market can be assumed to act competitively the equilibrium price of the market is said to be a *competitive equilibrium* or a *Walrasian equilibrium*. Whether emphasised or not, the theoretical foundation for the equilibrium prices discussed in this thesis is the notion of competitive equilibrium.

In real life it is often different. A market such as an electricity market,
is often dominated by a single actor or a small number of actors. As said elsewhere, historically we have viewed electricity markets as natural monopolies. These monopolies where typically controlled by the authorities. With liberalisation of energy markets this has changed, and the role of monitoring authorities has changed too. Today, often a few large players on supply side dominate electricity markets. That is, the market power of these actors is so large that it clearly influences market prices. There is an ongoing discussion in the Nordic countries as elsewhere on the effect of this market power. Theory refers to the situation as an oligopoly.

4.5 E-Markets

E-commerce and electronic trading have attracted a lot of interest in recent years both commercially and in the research community. On the consumer level anyone with a connection to the Internet may have visited electronic book shops such as Amazon.com, auction sites such as eBay, and search services claiming to search e.g. the electronic book shops to present the best price offered on a book that you want. In professional B2B contexts the examples might be quite different, often it is easier to identify them as resource allocation problems; the examples include supply chain formation, scheduling problems, etc.

Some of the extreme commercial interest in particularly business-to-consumer (B2C) aspects of e-commerce has disappeared in the turbulence of the last years, but the area is still of interest, even if more of the focus currently is on B2B e-commerce relations.

Electronic markets, computational markets, or agent based market negotiations are a relatively new concept. The first attempts to use electronic markets for resource allocation problems occurred within the domains of computer usage. As processor time was a limited and expensive resource, (pseudo) market models where developed for allocation of the resource [39]. Today a focus in this community is on communications, with market based approaches to handling of network resources, e.g. routing problems and problems related to different needs of communication quality (fast, reliable, etc.) [36, 37].

The main field that attracts commercial interest today is electronic markets focused on B2B relations. Freight scheduling, airport scheduling, supply chain formation, and usage of advanced combinatorial auction concepts are examples on problems that have attracted commercial interest and interest from the research community [3, 45, 46, 48, 49].
Many concepts are based on agent technology, i.e. systems of independent electronic agents negotiating on behalf of market participants. Research is focused on both agent behaviour and on system properties, and further on construction of both.

4.6 E-markets — The Final Solution?

Sometimes we tend to present results such that it seems as if we believed that they are more or less the answer to everything. We do not believe that electronic markets and computer aided resource allocation in general are such general answers to whatever questions and problems we encounter. Still, we believe the concepts to be valuable tools useful in large numbers of problems domains.

In society there is often a clash between different interests when it comes to resource allocation in general, often expressed by use of different measures used to evaluate for example market outcome. Electronic markets applied to the energy sector and utilised to introduce new actors on dynamic markets does not solve all the problems or change the fact that different groups have different interests, etc. On the other hand, a broad introduction of end user participation for example on day-ahead power market would certainly change the scene, and we believe that electronic markets are the instrument for such a change.
Chapter 5

Contributions

5.1 In the Thesis

In this thesis we present one article on general resource allocation and one on how to handle non-continuous demand on markets. Two papers deal with multi-commodity markets, one presents market simulations and one presents a field test on communications of market information.

5.1.1 Resource Allocation with Wobbly Functions

The first article in the thesis is on resource allocation. It has been published in Computational Optimization and Applications, 2002 [2]. A conference paper on the work was presented at The 5th International Workshop on Algorithm Engineering, WAE 2001, Århus, Denmark. Co-authors are Arne Andersson and Fredrik Ygge.

This work is applicable to electronic markets as market problems can be viewed as optimisation problems. We emphasise that it covers a more general optimisation problem that is not restricted to market optimisation.

In this work we consider resource allocation with separable objective functions defined over subranges of the integers. While it is well known that (the maximisation version of) this problem can be solved efficiently if the objective functions are concave, the general problem of resource allocation with functions that are not necessarily concave is difficult.

In this article, we focus on a large class of problem instances, with objective functions that are close to a concave function or some other smooth function, but with small irregularities in their shape. It is described that these properties are important in many practical situations.
The irregularities make it hard or impossible to use known, efficient resource allocation techniques. We show that, for this class of functions the optimal solution can be computed efficiently. We support our claims by experimental evidence. Our experiments show that, for hard and practically relevant cases, our algorithm runs up to 40 – 60 times faster than the standard method.

5.1.2 Extending Equilibrium Markets

The second article is on single commodity equilibrium markets. Published in IEEE Intelligent Systems, 2001 [9]. Co-authors Arne Andersson and Fredrik Ygge.

Equilibrium markets, which attempt to optimise the match between supply and demand, are drawing considerable interest among computer scientists — for example, for solving routing problems in communication networks, improving power control, and handling transportation planning. General equilibrium analysis and computation from classical economics has inspired the design of a number of market mechanisms. These mechanisms estimate a clearing price (such that supply meets demand for every commodity) and then reallocate those commodities according to the clearing price bids.

Challenging problems related to the construction of market mechanisms remain. For example, how do we deal with distributed information on large computational markets? Also, what do we do about discontinuous supply and demand?

In answer to these concerns, we developed a mechanism called Confast for highly dynamic equilibrium markets that allows for huge numbers of active market participants, even if they have discontinuous supply and demand curves. Because of its computational efficiency, our approach also works in markets with short time frames.

5.1.3 Communication Tests of Electronic Power Markets through Power Line Communication

Third is a paper on field experiments on communications performed in Lugano, Switzerland. The paper was presented at the conference Power Systems and Communications Infrastructures for the Future, arranged by The International Institute for Critical Infrastructures (CRIS) [14] in Beijing, September 2002 [11].
Current power systems poorly take advantage of the flexibility of the load side. One way to improve this is to let the loads respond to price changes. In most cases this process needs to be highly automated to make economic sense. We envision a scenario where “intelligent loads” take prices into account and adapt the consumption accordingly, and use the term electronic power markets to denote a system with automated trading loads.

A fundamental requirement for electronic power markets to become a commercial reality is access to inexpensive and relatively reliable communication (whereas the requirements on bandwidth are rather moderate). The field trials that we present were performed to investigate (from a technical point of view) whether Power Line Communication (PLC) is a potential candidate as communication means for this application. This field trial differs from most other field tests in this area as it: (i) uses medium voltage (6-20kV) cables as communication means (whereas most other tests are performed on the low voltage line), and (ii) focuses a narrowband communication system (rather than a broadband system).

The preliminary conclusion from the field trials is that medium voltage PLC is well suited for electronic power markets. Preliminary, because the
field tries have been performed in a limited scale and in an area where
the distances were moderate (up to some 4km). Further tests are thus
required, but the results so far are promising.

5.1.4 A Tractable Mechanism for Time Dependent Mar-
ketds

Fourth is an article on a multi-commodity market mechanism designed
with time-dependent markets in mind. The work was presented with
a short paper at the IEEE International Conference on E-Commerce,
CEC 2003, Newport Beach, California, June 2003 [10]. Co-authors are
Arne Andersson and Fredrik Ygge.

Markets with time dependent goods are special cases of multi com-
modity markets. The design of large flexible markets with time dependent
goods is a computational challenge. In the article we present a computa-
tionally tractable mechanism for time dependent markets. By a number
of predefined bid types, it offers useful flexibility to the bidders.

We present the market mechanism and the corresponding matching
algorithm together with some analysis of its behaviour. The algorithm
computes market prices efficiently.

5.1.5 A Flexible Model for Tree-Structured Multi-
Commodity Markets

The fifth article is another work on multi-commodity markets. The article
presents a number of results on tree-structured auctions and markets. The
article is submitted for journal publication. Co-author Arne Andersson.

In this article we study tree-structured multi-commodity markets. The
concept is a way to handle dependencies between commodities on the
market in a tractable way. The winner determination problem of a general
combinatorial market is well known to be NP-hard. It has been shown
that on single-unit single-sided auctions with tree-structured bundles the
problem can be computed in polynomial time.

We show that it is possible to extend this to multi-unit double-sided
markets. Further it is possible to handle the commodities of a bundle
not only as complements but as perfect substitutes too. Under certain
conditions the computation time is still polynomial.
5.1.6 Market Simulations

The last paper is a report on simulation work. The simulations are part of the work on novel market-based methods for supply – demand matching within the CRISP project.

The report covers a first set of simulations using our previously developed CONSEC algorithm on the time-scale of day-ahead power markets. Furthermore it describes simulations under preparation within the project.

The main purpose of the first simulations was to test the algorithm against the simulation setup. The results verify that a market based on the CONSEC mechanism works properly and that the algorithm handles the market efficiently.

5.2 Other Published Work and Reports

Two conference contributions that are not part of this thesis are:


I have some contributions in public reports from the EU sponsored PALAS\(^1\) and CRISP projects. They are in the following reports:

- PALAS:

\(^1\)PALAS: Powerline as an Alternative Local Access
Powre Line Communication over the middle voltage network for efficient Energy Distribution and Grid Management [33].


• CRISP:

Chapter 6

Conclusions and Future Work

6.1 Future Work

Current and future work within the CRISP project is focused on market simulations as reported in Paper Six, these simulations are joint work of EnerSearch and ECN, The Netherlands. We hope to show advantages of e-markets as a means for supply – demand matching (SDM) as well as to further develop our understanding of problems and difficulties.

Another focus is on the concept of “intelligent load shedding” (ILS), and we hope to be able to develop a market approach to ILS applicable to situations where the time constraints permit communications with end users. If we could utilise e-market structures built for SDM to handle emergency load reduction this is highly interesting.

6.2 Conclusions

Full scale electronic power markets are a shift of paradigm, maybe in the order of the shift from monopolistic utilities to liberalised power markets. We can identify steps that could be taken in the direction of these markets; one that we discuss in this thesis is price-reactive optimisation among end users, Chapter 3. Another one is small local markets, e.g. within low voltage cells and middle voltage cells with both consumption and production capacity, Paper Six.

The main contribution of ours is a number of algorithms designed to handle problems of interest in electronic markets. Further we relate theory to practice through tests and simulations. The main focus is on
electricity markets, but the algorithms may be well suited for application to other areas as well. Market problems that we cover span from handling non-continuous demand on markets to structuring of multi-commodity markets. The scope of one of the papers is not limited to electronic markets, but covers a more general optimisation problem.

Hopefully the work presented in this thesis contributes to the development of tomorrow’s power markets. We find electronic power markets a highly interesting concept, interesting both from a system viewpoint and from end user perspective, and believe that it has the potential to be a win-win concept. Further we note that electronic markets that promote more efficient utilisation of limited resources also have positive environmental impact.

Electricity is a limited resource with high and increasing importance to society and in our everyday life. The development of market concepts for electricity is vital. Electronic power markets have the potential to be a major contribution to efficient handling of electricity and we hope that the work and ideas presented in this thesis has an impact on society.
Acknowledgements

Even though it is easy to believe that it is so when writing a thesis, no man is an island. You would not hold this thesis in your hands would it not have been for the support from a number of persons, projects, companies, and within the universities of Uppsala and Lund.

Institutions

The the Information Technology Department at Uppsala University and the ones I have met there are the first to mention. As I have not been living in Uppsala the contact with my deparment has sometimes been sparse over these years, but it has still been essential. As I live in Lund, the Computer Science Department at Lund University has provided me with an office and the everyday contact with colleagues, as well as challenges in the form of teaching duties.

I am truly happy for both departments and most of all the people that fill them with life.

My work has been financially supported by a number of institutions; first it was supported by a part of NUTEK\footnote{The Swedish Business Development Agency.} [30] that is now VIN-NOVA\footnote{The Swedish agency for Research and Innovation for Sustainable Growth.} [44]. After this SITI\footnote{The Swedish Research Institute for Information Technology} [38] gave a financial support. Finally it is Sydkraft Research Foundation [40] that has supported my work during the last years.

I am grateful for this support.

From the start of my PhD studies I was employed at the department in Uppsala. This was changed in January 2002 when I was employed by EnerSearch to work within the EU sponsored CRISP project.
It is a privilege to work in EnerSearch as it is a small research oriented company with a number of share holders from the energy industry. The share holders of EnerSearch are ABB Automation Products, the Energy Research Centre of the Netherlands (ECN), Electricidade de Portugal (EDP), Eneco, Iberdrola, IBM Utility Services, E.ON-Energie, and Sydkraft. This connection to the industry is highly valuable.

A number of other companies have shown interest in the work and been supportive in different ways. I want to mention one of them; AIL, the power utility in Lugano that hosted the test equipment we used for the communication tests reported in Paper Three.

The CRISP Project

Taking part in the work of EnerSearch and the CRISP\(^4\) [15] project gives me as a computer scientist deeper insights in how problems are formulated within the energy industry. A citation from the CRISP web site describes the project:

"The CRISP project aims to investigate, develop and test how latest advanced intelligence by ICT technologies can be exploited in a novel way for cost-effective, fine-grained and reliable monitoring, management and control of power networks that have a high degree of Distributed Generation and RES penetration. The opportunities for interactive power networks to create new possible control mechanisms that create flexibility and self-managing networks will be shown. Normal and emergency operations are investigated covering different time scales. Insight in performance, security and architecture of highly distributed systems will be made available. Technical availability, functionality and economic cost-benefit considerations will be integrated. Results will contribute to better regional monitoring and control of local distribution in the EU-network."

Parts of the work within the project work focused how we can use electronic markets (i) to support balancing of power grids with distributed responsibilites as well as (ii) for emergency actions to increase or restore power system stability. This is where my efforts fit in.

\(^4\)CRISP: Distributed intelligence in critical infrastructures for sustainable power
6.2 Conclusions

All work and discussions in the project, together with colleagues of different background are of great value.

People

First of all I want to mention Arne Andersson and Fredrik Ygge. Thanks for all advice, guidance, work with papers, etc.

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From the days of the PALAS project I want to mention Joseph Lehmann, Göran Lindell, and Stefan Höst.

Related to the computer science department in Lund there are to many that ought to be mentioned. I pick a few (some of them are not at the department any more): Thore, Kris, Andrzej, Christos, Ola, Peter, Tomas, Jakob, Lars, Christian, Sonja, Eivor, Annika, Anne-Marie, Lena. Further among all present and former PhD candidates: Mattias, Per F., Magdalene, Eva-Marta, Sławomir, Mats Petter, Paul, Martin, Mia, Andreas, Anna Ö. Björn, Jesper, Joachim, Kurt, Mikael, Anders D., Anders S. In Uppsala Marianne Ahme has been of great help not least with practical information when I finished my thesis work.

All my friends that are not mentioned explicitly... Thank you all for your support and friendship!

Special thoughts and thanks go to my parents Ingrid and Oscar, my two children Jakob and Anna, and their mother Ewa, my brother Torsten and his family, my sister Margaretha and her family, and Gun-Marie.

Thank you all, for support, advice, cooperation, friendship... for being who you are!
Summary in Swedish

Resursfördelningsfrågor är ständigt aktuella inom livets alla områden, globalt såväl som i det personligt nära. Beroende på sammanhang hanteras dessa frågor på olika sätt och vi betraktar dem utifrån olika perspektiv; etiskt, politiskt, ekonomiskt osv. Ett viktigt verktyg som är ”naturligt” i många sammanhang är marknader av olika slag. På en marknad priset det instrument som styr resursfördelningen och i princip styrs marknads-priset av relationen mellan tillgång och efterfrågan.

Elektroniska marknader är ett relativt nytt uttryck. Att en marknad är elektronisk är ett tekniskt begrepp som säger att den på ett eller annat sätt hanteras med hjälp av datorer och datornätverk som Internet. Som enskilda har vi kanske erfarenhet av nätbokhandlar, auktionssajter eller Internettjänster som är inriktade mot prisjämförelser eller fungerar som mötesplatser för secondhandförsäljning. I relationen mellan företag kan elektronisk handel ha andra förtecken, typiskt handlar det om effektiv upphandling av tjänster och varor.

Bland datavetenskapligt intressanta marknadsproblem finns hur man beräknar vinnande bud på komplexa auktioner och hur man beräknar jämviktspriser på olika typer av marknader.

Resursfördelning i allmänhet och elektroniska marknader i synnerhet är i fokus för denna avhandling. I avhandlingen presenteras ett antal algoritmer för resursallokering och elektroniska marknader. Vi kan applicera den här typen av algoritmer på många konkreta områden. I vårt fall ligger fokus på energiområdet, närmare bestämt på elmarknader.

I Sverige liksom i stora delar av Europa har elmarknaden avreglerats under senare år. Denna avreglering innebär att det s.k. naturliga monopoliet inom elmarknaden begränsats till nättjänster. Avregleringen gör att elleverantören konkurrensutsätts och elanvändaren får nya valmöjligheter.

På en viktig punkt skiljer sig elektricitet väsentligt från flertalet andra produkter. Vi kan inte lagra el på ett effektivt sätt. Därför måste tillgång
balansera efterfrågan i ett elnät i varje ögonblick. Samtidigt varierar tillgången på el, och än mer efterfrågan, både med säsong och över dygnets timmar. En effekt är att priset på den sista kilowatttimman, marginalpriset, kan skillja mycket från timme till timme.

En brist hos dagens elmarknader är att slutanvändarna\textsuperscript{5} nästan uteslutande har kontrakt med fast elpris, ett pris som alltså inte följer det aktuella priset t.ex. på NordPools spotmarknad\textsuperscript{6} direkt. Detta gör att marknaden saknar instrument för att tillgodogöra sig den \textit{flexibilitet} som finns hos dessa aktörer. Alltså att (i) konsumenter kan ändra sitt konsumtionsmönster för att sänka sin elkostnad och (ii) småskalig produktion med begränsad kapacitet kan välja att producera när det är som mest lönsamt, d.v.s. när marknaden säger att behovet är som störst. Typiska konsumenter med en relativt stor flexibilitet använder el för uppvärmning och kylning. Motsvarande flexibilitet finns hos småskalig elproduktion. Småskalig produktion väntas bli allt vanligare i Europa under de närmaste åren.


En förhoppning är att denna avhandling ska kunna bidra till utvecklingen av framtidens elmarknader.

\textsuperscript{5}I begreppet slutanvändare inkluderar vi konsumenter och småskalig elproduktion.

\textsuperscript{6}NordPools spotmarknad är en s.k. “day-ahead market” där den el som ska levereras nästa dag handlas på timbasis.
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A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to October, 1993, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science”.)