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Effektiviteten i det europeiske kraftmarkedet:

Et tiltak for å inkludere fleksibilitet fra termisk kraftproduksjon

Erik Brendbekken Rudlang
Carl Fredrik Tjeransen

Industriell økonomi og teknologiledelse
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Hovedveileder: Stein-Erik Fleten, IØT
Medveileder: Gro Klæboe, Powel

Norges teknisk-naturvitenskapelige universitet
Institutt for industriell økonomi og teknologiledelse

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MASTERKONTRAKT
- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn **Rudlang, Erik Brendbekken**	Fødselsdato **17. jan 1988**
E-post **erudlang@gmail.com**	Telefon **93691325**

2. Studieopplysninger

Fakultet **Fakultet for samfunnsvitenskap og teknologiledelse**	
Institutt **Institutt for industriell økonomi og teknologiledelse**	
Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Anvendt økonomi og optimering**

3. Masteroppgave

Oppstartsdato **15. jan 2014**	Innleveringsfrist **11. jun 2014**
Oppgavens (foreløpige) tittel **Effektiviteten i det europeiske kraftmarkedet:** **Et tiltak for å inkludere fleksibilitet fra termisk kraftproduksjon**	
Oppgavetekst/Problembeskrivelse Uforme en markedsklareringsalgoritme for kraftmarkeder. Analysere forbedret markedsklarering som følge av eksklusive grupper og fleksible blokker ved hjelp av algortimen.	
Hovedveileder ved institutt **Professor Stein-Erik Fleten**	Medveileder(e) ved institutt
Ekstern bedrift/institusjon **Powel**	Ekstern veileder ved bedrift/instutisjon **Gro Klæboe**
Merknader **1 uke ekstra p.g.a påske.**	

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

TRONDHEIM 25/4 -14

Sted og dato

Erik Rundberg (signature) — **Student**

Stein-Erik Fleten (signature) — **Hovedveileder**

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MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn	Fødselsdato
Tjeransen, Carl Fredrik	**06. jul 1980**
E-post	Telefon
cftjeransen@hotmail.com	**92411483**

2. Studieopplysninger

Fakultet **Fakultet for samfunnsvitenskap og teknologiledelse**	
Institutt **Institutt for industriell økonomi og teknologiledelse**	
Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Anvendt økonomi og optimering**

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Hovedveileder ved institutt **Professor Stein-Erik Fleten**	Medveileder(e) ved institutt
Ekstern bedrift/institusjon **Powel**	Ekstern veileder ved bedrift/instutisjon **Gro Klæboe**
Merknader **1 uke ekstra p.g.a påske.**	

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Trondheim 25.04.14
Sted og dato

Carl Fredrik Tiesen
Student

Stein-Erik Fleten
Hovedveileder

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SAMARBEIDSKONTRAKT

1. Studenter i samarbeidsgruppen

Etternavn, fornavn	Fødselsdato
Rudlang, Erik Brendbekken	**17. jan 1988**
Etternavn, fornavn	Fødselsdato
Tjeransen, Carl Fredrik	**06. jul 1980**

2. Hovedveileder

Etternavn, fornavn	Institutt
Fleten, Stein-Erik	**Institutt for industriell økonomi og teknologiledelse**

3. Masteroppgave

Oppgavens (foreløpige) tittel
Effektiviteten i det europeiske kraftmarkedet: **Et tiltak for å inkludere fleksibilitet fra termisk kraftproduksjon**

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Kandidatene skal ha *individuell* bedømmelse ☐
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Trondheim 25.04.14
Sted og dato

Erik Rudlang
Erik Brendbekken Rudlang

Stein-Erik Fleten
Hovedveileder

Carl Fredrik Tjeransen
Carl Fredrik Tjeransen

Originalen oppbevares på instituttet.

Abstract

Power consumption needs to shift from conventional power sources such as coal and gas and move towards renewable energy sources (RES) that have less damaging effect on the environment. This transition is happening in a number of European countries. RES are intermittent by nature, which increases the volatility in the power markets. This complicates the bidding process as prices are much harder to predict. The market may lose both its ability to serve the market participants' needs and its attractiveness as a marketplace. This thesis analyzes the structural changes and proposes policy changes for the day-ahead market in Europe. The rigid structure of the day-ahead market amplifies the market volatility. To handle large variable external forces, the system needs to be more dynamic and flexible. Two new products are analyzed that will increase the flexibility in the market, and support increased shares of RES. When these products are implemented, prices are moderated, market efficiency increases, and the market outcome will more closely reflect a competitive equilibrium where market participants are satisfied with their own decisions given the market outcome.

Sammendrag

De er nødvendig å redusere kraftproduksjon fra tradisjonelle energikilder som kull og gass og øke andelen ny fornybar kraftproduksjon som ikke skader miljøet. Dette skiftet skjer i flere Europeiske land. Fornybar kraftproduksjon er uforutsigbar og medfører derfor økt prisvolatilitet i kraftmarkedet. Dette kompliserer budgivingsprosessen, siden det blir vanskeligere å forutse prisene. Kraftmarkedet kan derfor miste sin attraktivitet og evne til å tilfredsstille markedsaktørenes behov. Denne masteroppgaven analyserer de strukturelle endringene økt fornybar energiproduksjon medfører og foreslår endringer i kraftbørsenes regler. Den rigide strukturen i kraftmarkedet forsterker pris volatiliteten. For å håndtere store og variable ytre krefter trenger systemet å være mer dynamisk og fleksibelt. To produkter som vil øke fleksibiliteten i markedet og støtte økt andel av ny fornybar kraftproduksjon er analysert. Implementeringen av disse produktene vil medføre mindre prisvolatilitet, økt markedseffektivitet og en markedsklarering som er nærmere en markedslikevekt hvor alle deltakerne er fornøyd med egne beslutninger markedsløsningen tatt i betrakting.

Preface

This is a master thesis written within the field of Applied Economics and Operations Research at the Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU). The authors would like to thank Stein-Erik Fleten and Gro Klæboe for their guidance and insight into the problem at hand, Christian Skar for technical assistance, FICO for access to their Xpress solver, EPEX SPOT for valuable market data, Powel AS for providing us with office space and nice facilities, and our families for support during our studies.

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Erik B. Rudlang

Carl Fredrik Tjeransen

Contents

Chapter 1

Introduction

The main research question addressed in this thesis is:

How can the efficiency of the European day-ahead market be improved under the new conditions of high RES (Renewable Energy Sources) in the European power market?

A series of sub-questions follow:

1. How can additional products increase the efficiency of the day-ahead market?
2. How can these products be implemented in the market-clearing algorithm?
3. How can the efficiency and reliability of the market-clearing algorithm be improved to support a set of complex bid products?

This thesis proposes changes to the European power exchanges' market policies by implementing two block bid products. A new market clearing algorithm is presented to support these products. Realizing these policy changes will increase the efficiency of the market and support a fairer day-ahead market. The main contribution of this thesis is two papers. Article 1, ”A Branch-and-Cut Algorithm to Clear the European Day-Ahead Power Market”, and Article 2, ”Increasing the Efficiency of the European Day-Ahead Power Market using Exclusive Block Groups and Flexible Volume Blocks”.

There is considerable interest and funding flowing to research projects that focuses on energy research and innovation. The Research Council of Norway has established the ”The Large-Scale Programme for Energy Research” (ENERGIX). The programme is set in place to promote research on renewable energy, efficient use of energy, energy systems, and energy policy [1]. In the European Union, Framework Programme for Research and Innovation, Horizon 2020 [2] is the largest programme to date in the EU. 79 billion euros are made available to address the key societal challenges; secure, clean, and efficient energy. This thesis researches the efficiency of the European day-ahead markets and proposes changes to the market design of the day-ahead market, more specifically changes to the product offering at European power exchanges.

The first chapter of this thesis gives an overview of the market design and the role of day-ahead markets. The structural changes of the power market is discussed in Chapter 3. The bidding problem for thermal power producers is presented in Chapter 4. The final chapter discusses the consequences when the design of the day-ahead market does not reflect the needs of the market participants.

An efficient and reliable market clearing algorithm is a condition for a well functioning day-ahead market. In Article 1 [3] a new market-clearing algorithm is developed that is able to solve the clearing problem up to 200 times faster than previously published algorithms. The algorithm does not suffer from numerical instability and provides a reliable tool for power exchanges to manage the market-clearing. This algorithm is extended in Article 2 to account for the two new bid types.

In Article 2 [4] it is found that structural changes due to increased shares of intermittent renewable energy production have made it harder for thermal power producers to give efficient bids in the day-ahead market. Two new bid products, the recently introduced exclusive block groups and the proposed flexible volume blocks are tested in their ability to remedy the situation and increase the efficiency of the market.

Both articles are planned submitted to IEEE Transactions on Power Systems.

Chapter 2

The Day-Ahead Market

The delivery of electricity from producer to consumer consists of a number of services such as transmission, generation, distribution and frequency control. The market design or architecture consists of the set of sub-markets that provide these services to enable a reliable provision of electricity [5]. Some common sub-markets are the day-ahead market, balancing markets, and capacity markets. One overview of different market designs worldwide is given in [6]. The European market design typically consists of a financial forward market, a day-ahead market, an intra-day market, and markets for ancillary services.

Long-term bilateral financial markets give power generators the possibility to hedge future electricity prices. The day-ahead market is organized either as a pool or an exchange, while the intra-day market is a bilateral market. These markets use standardized contracts and rules to establish a set of prices that clear the market. The prices established by the day-ahead auction provide an important basis for additional markets such as the financial forward market and private bilateral markets. Even though only a fraction of gross energy production is traded in the day-ahead market in some European countries (see Table 2.1), the price signal will have a wider impact. An efficient market design is therefore highly important to send correct signals.

The day-ahead market is designed to clear the market in sufficient time before actual production to coordinate less flexible resources in the market. A number of generation technologies have technical restrictions that make it necessary for unit commitment choices to be made ahead of time. There are two main designs for the day-ahead market. In a power pool unit commitment decisions are made centrally by the market operator on behalf of market participants. In a power exchange unit commitment decisions are decentralized to the generators, and the market operator will select the commitment decisions that maximizes social welfare. The pool model is used

Table 2.1: Overview of power exchanges in North Western Europe with markets offered, volumes traded, and gross total generation [7–9]

	Volumes [TWh]		
Power Exchange	**Day-ahead (2013)**	**Intra-day (2013)**	**Total Generation (2012)**
Nord Pool Spot	**348.9**	**4.2**	**438.67**
Norway			147.84
Sweden			166.56
Finland			70.39
Denmark			30.72
Estonia			11.96
Latvia			6.16
Lithuania			5.04
EPEX SPOT	**322.8**	**23.1**	**1270.50**
Germany			629.81
Austria			72.61
Luxembourg			3.81
France			564.27
Belpex	**17.1**	**0.66**	**82.87**
Belgium			82.87
APX NL	**47.3**	**0.73**	**102.50**
Netherlands			102.50
APX UK	**8.8**	**14**	**363.83**
UK			363.83
N2EX	**139.0**	**3.4**	**363.83**
UK			363.83

in a number of states in the U.S. [10], whereas the power exchange model is used in a number of European countries [11]. Participation in a pool is mandatory, and the market participants must schedule generation according to schedules provided by the market operator. The market operator determines these schedules by computing the optimal unit commitment decisions given the bids submitted to the market such that forecasted demand is served. The bids include technical and cost characteristics of the generators that the market operator includes in the optimization program. Power producers participating in a power exchange is individually responsible for the scheduling and unit commitment decisions. Producers and consumers submit bids to the market, and the market is cleared such that social welfare is maximized and the supply and demand is balanced.

In most European countries, a power exchange model is used [11].The main products traded at these power exchanges are hourly bids and block bids. An hourly bid is defined as a piecewise linear or stepwise price-quantity curve [12]. Hourly bids are used to signal marginal costs of production or marginal benefit of consumption to the auction. There exist a number of different types of block bids. These products are offered to account for non-convex economic and technical characteristics for some market participants. The different block bids offered at European power exchanges are simple blocks, linked blocks, and block bids in exclusive groups [12]. Traditionally only simple block bids consisting of a single price-quantity pair for a number of hours, with a "fill-or-kill" condition were offered. The "fill-or-kill" requirement means that either the block is fully accepted, or fully rejected. Recently more complex block order products have been introduced to European power exchanges. A profiled block allows power producers to tailor the volumes of the simple block to form a production profile. The power producer will thus be able to signal ramping requirements at start/stop for a generator. Linked blocks bids enable producers to specify a link between a number of simple blocks. A linked block is specified according to its position and will be accepted only when all prior blocks in the linked sequence is accepted. These blocks can be used to signal operating profiles dependent on an initial configuration. Exclusive block groups allow at most one block in a block group to be accepted. An exclusive block group can be used to signal alternative operating profiles to the market.

Chapter 3

The Changing Market Structure

The market structure consists of the properties of the market determined by long-term dynamics such as legislation, cost characteristics, power mix and technological change. The market structure will be specific for each individual power market, but some common characteristics are outlined below.

A lack of demand response is a common feature among most power markets [13]. This is because consumers generally pay a weighted average price of their consumption for a certain period. Consumers are therefore not faced with the dynamics of the wholesale price, and will be insensitive to the price changes. Electricity demand, as such is characterized by a predictive pattern. Variables affecting demand are outside temperature, the time of day and whether it is a working day or not. Price, however, has very little effect on this consumption pattern.

Power is generated from wide variety of technologies. The conventional generation consists of production from coal, natural gas, and nuclear power plants. These technologies are characterized by technical restrictions in ramping, start-up and shut-down of generators. Considerable start-up costs occur when these generators are started and they are consequently less suited to respond quickly to market changes. Conventional power generation accounts for a large share of power production in European countries (see Table 3.1). The inflexibility of these generators makes it necessary to plan production in significant time before actual production.

Renewable energy sources make up a more diverse set of technologies. These range from dispatchable energy production such as stored hydro and geothermal power, to non-dispatchable wind and solar power. Intermittent power from non-dispatchable sources must be balanced. How these generation

Table 3.1: Gross electricity generation by fuel in the EU (2011) [14]

	Generated	**Share**
Nuclear	906.8	27.6 %
Solid Fuels	848.7	25.9 %
Gasses	726.5	22.2 %
Renewables	699.5	21.3 %
Petroleum	73.6	2.2 %
Other	24.5	0.7 %
Total	**3279.6**	

technologies are allowed to participate in the power auction give important implications for the functioning and operation of the day-ahead markets. Most renewable energy generation is characterized by high investment costs, but low marginal cost due to the absence of fuel cost.

European countries are pushing to reduce greenhouse gas emissions and dependency on foreign energy sources. Policies to increase exploitation of renewable energy by giving it an economical advantage [15, 16] are therefore spreading. Large investments in renewable power production have led to dramatic changes in the underlying market structure. Figure 3.1 illustrates how the share of intermittent power generation capacity of the total available capacity increases. There have been different schemes for the adoption of these sources in the power mix. Germany has implemented a fixed "feed-in-tariff " system where generators receive a set tariff for each kWh of power delivered regardless of the market price [17]. Situations with low demand and high production can in this paradigm lead to negative market prices. When generators are not confronted with the market dynamics, price volatility increases since these generators are totally insensitive to market prices. The low marginal cost of renewable energy sources effectively lowers the price in the market. The effect has been studied in the literature [18, 19]. These volatile market conditions have complicated the unit commitment problem significantly for European power producers.

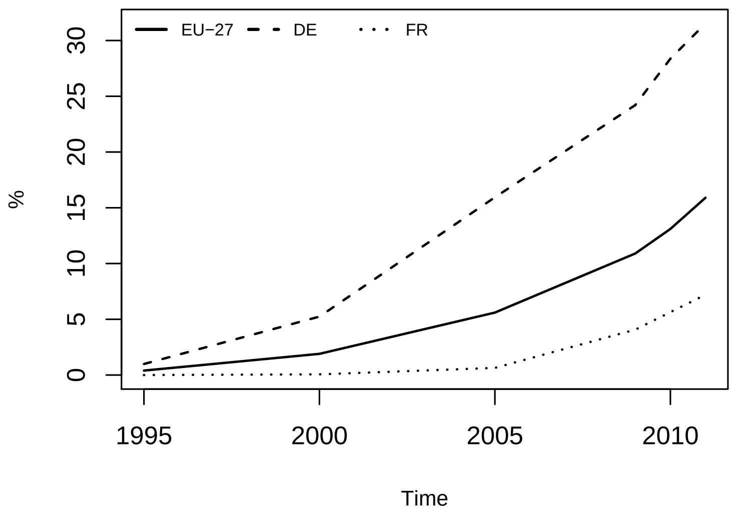

Figure 3.1: Share installed intermittet electricitiy production capacity of total installed capacity in the European Union (EU-27), Germany (DE) and France (FR). [14]

Chapter 4

Challenges in the Decentralized Unit Commitment Problem

In Europe the scheduling of production is decentralized to the market participants. Each generator is individually responsible for finding the optimal commitment decisions and submits bids that reflect these decisions. Due to technical restrictions in the start-up and shut-down of generators, unit commitment decisions must be made in significant time before actual production. To coordinate these activities the day-ahead closes 12 hours before production. There are a number of papers that research the optimal way for thermal power producers to bid into the day-ahead market. The problem of determining the optimal set of bids is called the profit-based unit commitment problem (PBUC) in academia to contrast this problem to the security constrained unit commitment problem (SCUC) solved by the power pools. The PBUC finds the commitment that maximizes the producers' profits based on the price expectancy for the next day [20]. The change in European market structure with increased shares of intermittent power production has led to more unpredictable power prices. When price volatility increases it becomes much harder to make good unit commitment decisions ahead of time. Thermal power producers must cover large start-up costs and ensure a commitment that does not violate the turbines' technical restrictions. This cannot be guaranteed with hourly bidding. Stoft [5] argues that generators should rather use block products to signal start-up costs to the market and thus ensure profitable and viable commitments. While there has been significant efforts to develop models that determine optimal bidding curves for hourly bids [21–23] there are few examples in the literature of optimal use of block bidding. One such example is [24].

The price of the block should cover the start-up cost (C^{start}) marginal cost (C^{marg}) and commitment cost (C^{com}). Revenue adequacy has been used to describe the need for thermal power generators to cover these costs [25]. The following example illustrates that there exists a number of different operating profiles and pricing strategies for the power producer.

The total cost of operating a turbine (C^{tot}) generating q_t MW per hour for $t_s - t_0$ hours after start up t_0) is given by the following equation.

$$C^{tot} = C^{marg} \sum_{t_0}^{t_s} q_t + \sum_{t_0}^{t_s} C^{com} + C^{start} \tag{4.1}$$

The price p that ensures revenue adequacy is given bellow:

$$p \sum_{t_0}^{t_s} q_t = C^{marg} \sum_{t_0}^{t_s} q_t + \sum_{t_0}^{t_s} C^{com} + C^{start} \tag{4.2}$$

$$p = C^{marg} + \left(\frac{\sum_{t_0}^{t_s} C^{com} + C^{start}}{\sum_{t_0}^{t_s} q_t} \right) \tag{4.3}$$

A number of production profiles and pricing strategies exist that satisfy the revenue adequacy requirement. For a given set of cost characteristics (C^{com}, C^{marg}, and C^{start}) the price p, start-up of the block t_0, the number of hours of the block $t_s - t_0$, and the volumes in each hour q_t can vary corresponding to (4.3). The most significant cost element for thermal power generation is the start-up cost. In (4.3) the start-up cost is divided by the total volume produced. The impact on price can therefore be reduced by producing high volumes. Since the output of the generator is limited, a high volume can be obtained only by aggregating volumes for a number of hours. At least two possible pricing strategies emerge. The lowest block price is obtained by spreading the start-up cost on the maximum hours in the market (base load block). A high priced block is obtained by restricting the number of hours of the block to a subset of hours in the next day (peak load block). Both of these pricing strategies might result in dispatch for the generator. When average prices are low, the base load block might be rejected, but a price peak in the same day will make the peak load block be accepted. When average prices are high, the base load block might be accepted, but stable prices will make the peak load block be rejected. The power producers should be allowed to specify both of these blocks as alternative production profiles to maximize their impact in the market. Traditional simple blocks, does not allow for alternative profiles to be specified. In Article 2 [4] the authors show how exclusive block groups and flexible volume blocks can be used to signal a range of different operating profiles.

Chapter 5

Design Defficiencies

The design of the day-ahead market consists of a number of considerations. These considerations include what kind of products to offer, the acceptance rules in the market, and the procedure of settlement [5]. This chapter discusses the potential effect on the market efficiency and overall function of the market when the products offered by the market operator are not aligned with the needs of the market participants.

The previous chapter illustrated that using simple blocks the power producers is not able to specify alternative operating profiles to the market. Consequently, when a simple block is used to value production in the next day, the power producer faces a significant risk of not being dispatched in the market even though a feasible operating profile might exist. Thermal power production is characterized by high fixed costs and it is essential for these producers to get dispatched if there exist an economically viable dispatch. The risk associated with simple blocks can be offset by submitting price-independent block bids, or submitting marginal cost curves. Price-independent block bids will be accepted in the market regardless of the market price. Marginal cost bids will be accepted if the price is equal or higher than the marginal cost of production.

Price-independent block bidding might ensure dispatch, but will make the bidder vulnerable to unexpected price drops that may leave the commitment unprofitable. Using marginal cost bidding, power producers face the risk of unfeasible commitments [26] and financial risk of not covering start-up costs. The first problem occurs because technical requirements in the production cannot be signaled with marginal cost bidding. If prices fall below marginal cost of the generator for a number of hours, the generator is without commitment for the respective hours. Inflexibility in the generator prohibits thermal power producers to quickly shut-down or start-up production. The system operator must balance the offset between actual production and market commitment and the power generator will be penalized. The second problem is due to marginal cost bidding not being able to signal start-up costs. A given dispatch might therefore not provide enough revenue to cover start-up cost. When marginal cost bidding is used to internalize the start-up costs, this leads to economic inefficiency and cross-subsidies [27].

In [28] it is found that block bidding only comprise a small share of bidding volumes on European power exchanges. This may be due to a number of factors. Power producers are not shown to behave rationally in the market [29], [30]. Traditionally, high and predictable prices in the day-ahead market made marginal cost bidding useful to ensure dispatch and cover start-up costs [5]. The recent growth in intermittent generation from renewable energy sources has caused price fall and increased volatility in some European markets. One consequence is the occurrence of large, hard-to-predict price drops, where prices can turn negative [31]. The consequence is that marginal cost bidding is not able to satisfy the needs of the power producers anymore. New products should be considered to allow market participants to effectively engage in the market.

When the products offered by power exchanges are not aligned to the needs of the power producers, the producers will try to compensate using alternative measures as described above. Stoft [5] shows that when only one-part bids are allowed, bidders will use randomized bidding strategies and tend to over-commit in the market to ensure start-up cost coverage. Additional hedging possibilities in an additional real-time market increases over-commitment even more. The welfare of the market will be affected. Inappropriate bidding may result in potentially large costs not being signaled to the market and a set of sub-optimal generators is committed to serve demand. When a suboptimal set of generators is committed, social welfare is reduced. If bids do not accurately reflect the bidder's costs, the resulting market commitment may be unprofitable or sub-optimal to the power producer. The market-clearing will therefore not constitute a competitive equilibrium. Dissatisfied bidders will find other markets, for example through bilateral contracting.

Chapter 6

Further Research

Producers with temporal and economical restrictions should be able to signal their operating opportunities effectively. Exclusive block groups are already available in several markets and flexible volume blocks may be implemented in the future. For these bids to become attractive they need to be easy to use. Future research might look at decision-support tools that can alleviate the power producers in the bidding process.

Power generators' bidding behavior is not well understood. A qualitative survey that identifies some of the underlying variables driving behavior in the market would be beneficial for policymakers and scholars. This survey could uncover the market participants' knowledge of market rules, and attitudes towards products and procedures.

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A Branch-and-Cut Algorithm to Clear the European Day-Ahead Power Market

Erik B. Rudlang, Carl Fredrik Tjeransen

***Abstract*—Power exchanges in the European electricity markets need to clear the physical day-ahead power auctions with sufficient speed and reliability. This paper proposes a branch-and-cut algorithm to solve the market-clearing problem and benchmark this algorithm against two previously published solution methods. The proposed algorithm solves the problem instances significantly faster than the two other algorithms, and does not suffer from numerical instability issues associated with the big M approach. The algorithm is also able to divide surplus equally among producers and consumers when prices are not uniquely determined by the bid selection, resulting in a fairer market-clearing.**

***Index Terms*—Combinatorial auction, Electricity market clearing, Integer linear programming, Power system economics, Market research**

NOMENCLATURE

Sets

I	Set of hourly bids
I^S	Subset of supply bids $I^S \subset I$
I^D	Subset of demand bids $I^D \subset I$
J	Set of block bids
J^S	Subset of supply bids $J^S \subset J$
J^D	Subset of demand bids $J^D \subset J$
T	Set of time steps
B	Set of bids

Indices

i	Index of hourly bids
j	Index of block bids
t	Index of time steps

Variables

x_{it}	Acceptance of hourly bid i in time step t
y_j	Binary variable; 1 if block bid j is accepted else 0
s_{it}	Dual variable for on upper bound of x_{it}
s_j	Dual variable for on upper bound of y_j
p_t	Market price in time-step t
β_{it}	Binary variable; 1 if hourly bid i is accepted else 0
δ_{it}	Binary variable; 1 if hourly bid i is totally accepted else 0
r_j	Slack variable on the acceptance bound of block bid j

The authors are with Norwegian University of Science and Technology (NTNU), Trondheim, Norway (e-mail: erudlang@gmail.com, cftjeransen@hotmail.com).

Bid Parameters

Q_{it}	Hourly bid volume for bid i in time-step t
Q_{jt}	Block bid volume for bid j in time-step t
P_{it}	Hourly bid price for bid i in time-step t
P_j	Bid price for block bid j

Algorithm Parameters

P_{max}	Price cap set by market operator
P_t^U	Upper price limit for the incumbent solution
P_t^L	Lower price limit for the incumbent solution
M	Large value
m	Small value

I. INTRODUCTION

ELECTRICITY is a vital commodity in modern society. Efficient and reliable clearing of the day-ahead electricity market is therefore highly important. The electricity auctions take place every day all year round and in 2013 322.8 TWh power was traded at a value of more than 12 billion euros through EPEX SPOT alone [1].

European power exchanges are organized as two sided single sealed bid auctions. Both electricity suppliers and consumers reflect their value through a set of bids. The market operators collect the bids and select the bids that clear the market and maximize social welfare, i.e. consumer and supplier surplus. Thermal power production is characterized by high start-up costs and technical restrictions such as maximum change in output (ramping), minimum run-times and minimum stand-still times. Signaling the electricity production cost can therefore be challenging. Power exchanges have introduced block products to allow these producers to signal non-convex characteristics. The discrete nature of these block products complicates the market-clearing significantly. The resulting problem is a mixed-integer combinatorial problem which is generally hard to solve [2].

The market operator needs to determine prices that clear the market. Linear prices that clear the market in the classical economic sense do not exist due to the non-convex characteristics of the electricity market. How prices are determined depends on the market design. In the U.S. the resources are pooled together and scheduled centrally by the system operator. Participation in the pool is mandatory and a set of prices must be established such that no market participant experiences a loss due to the market-clearing. In the U.S side-payments are made to some bidders to ensure a competitive market outcome [3]–[6]. The European philosophy is that all market participants should receive the same price, and the acceptance rules should prevent any bids from being unprofitable [7].

A number of different algorithms have been used to solve the market-clearing problem in Europe. Due to the complexity of the problem, a number of heuristics was initially used to obtain a feasible clearing in sufficient time. The main heuristic algorithms are Sapri and TLC [8]. A heuristic algorithm cannot guarantee that the optimal solution is found, this is problematic for the market-clearing problem. Social welfare might not be considerably affected, but the algorithm will reward a different set of generators in the heuristic solution compared to the optimal solution. This raises fairness issues. Sapri was used in the N2EX market until it was replaced by Euphemia in 2014 [9], and TLC was replaced by the COSMOS algorithm in 2010 [10]. COSMOS was the first algorithm that was able to solve the market-clearing problem to optimality. The current algorithm used by major European power exchanges is the market-coupling algorithm Euphemia [11] implemented in February 2014. This algorithm couples the day-ahead markets across Central Western Europe, Great Britain, the Nordic and the Baltic countries, and the SWEPol link.

In this paper the authors present a new market clearing algorithm with a branch-and-cut procedure. This algorithm solves all instances to optimality upto 200 times faster than previously published algorithms. The algorithm also allows for more control on pricing in cases where prices are undetermined.

This paper is organized as follows. Section II presents the general mathematical formulation of the European market clearing problem. Section III discusses different solution methods proposed in the literature. Section IV presents the new solution algorithm avoiding some of the problems with the proposed solution algorithms. In Section V the solution algorithms are compared based on actual market data from EPEX SPOT. A discussion of the results is provided in Section VI, and a conclusion follows in Section VII.

II. The European Market-Clearing Problem

The market-clearing problem is sometimes called a matching problem [12]. In the matching problem the set of supply and demand bids are matched to maximize social welfare of the market. Due to the non-convex block bids this is a combinatorial optimization problem which is generally hard to solve. Combinatorial problem solving rely on efficient solution algorithms as the solution time increases exponentially with the number of bids [2].

A more detailed model of the day-ahead clearing problem for power exchanges includes Available Transfer Capacities (ATC) [8], [13]. The ATC Problem includes a model of the transmission network. This model is commonly used by power exchanges to calculate area prices [13]. However, this model does not the physical flow of power as it is described by Kirchoff's laws. Consequently, power can flow in different directions than that predicted from the ATC model. The DC Power Flow model can be used for a better modeling of the transmission network, this is discussed in [14]. This paper is concerned with the combinatorial matching problem and its efficient solution algorithms. The model does not include network effects, and corresponds therefore to a single bidding area.

Matching Problem

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt}P_j \qquad (1)$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \qquad [p_t\,] \qquad (2)$$

$$x_{it} \leq 1 \qquad [s_{it}] \qquad (3)$$

$$y_j \leq 1 \qquad [s_j\,] \qquad (4)$$

$$x_{it} \geq 0 \qquad (5)$$

$$y_j \in \{0,1\} \qquad (6)$$

The objective function (1) describes the social welfare in the market. Q_{it} and Q_{jt} are defined such that demand bids are positive and supply bids are negative. Equation (2) specifies that the balance of supply and demand must be fulfilled in each hour. Equation (3) set the upper limit on the acceptance of hourly bids. Consequently an hourly bid can be totally accepted, partly accepted or totally rejected. The block bids consist of a single volume for each hour of the block that is either totally rejected or totally accepted. This requirement is modeled by (6). Relaxing the integer requirement for block orders (6), dual variables p_t, s_it, s_j exist. The dual variable p_t on (2) corresponds to the marginal value of power i.e. the market price. s_ij and s_j are the surplus variables corresponding to the respective bids.

Complementary slackness (CS) conditions specify optimality requirements for LP problems. The CS conditions corresponding to the linear program (LP) of the matching problem is shown below (7)–(10).

$$s_{it}(1 - x_{it}) = 0 \qquad (7)$$

$$s_j\,(1 - y_j\,) = 0 \qquad (8)$$

$$x_{it}(s_{it} + Q_{it}p_t - Q_{it}P_{it}) = 0 \qquad (9)$$

$$y_j\left(s_j\, + \sum_{t=1}^{T} Q_{jt}p_t - \sum_{t=1}^{T} Q_{jt}P_j\right) = 0 \qquad (10)$$

$$s_{it}, s_j \geq 0 \qquad (11)$$

The practical understanding of these equations is that all profitable bids must be included in the optimal solution $s_{it} \geq 0$ $s_j \geq 0$, and no unprofitable bids can be included in the optimal solution. The optimality conditions in (7)-(10) do generally not hold for integer problems, so linear prices, p_t, does generally not exist that correspond to primary variables. In particular, the set of restrictions will be infeasible due to restrictions (8) and (10). The power exchange must determine a set of prices to compensate the market participants. One approach for finding a set of prices is therefore either to relax (8) or (10). The prices obtained by either relaxation will not constitute a set of competitive prices in the classical economic sense, but provide a set of prices that can clear the market. There are different consequences of relaxing either (8) or (10). When (8) is relaxed, the requirement that $s_j = 0$ when $y_j = 0$ is omitted. The practical understanding is that there might exist a profitable market opportunity $s_j \geq 0$ for a block bid j even though the block bid is not accepted in the market-clearing $y_j = 0$. Such a block bid is called a paradoxically-rejected-block (PRB). If (10) is relaxed the relation $s_j + \sum_{t=1}^{T} Q_{jt}p_t - \sum_{t=1}^{T} Q_{jt}P_j = 0$ is not necessarily satisfied when a block bid is accepted in the market-clearing $y_j = 1$, The result is that a bidder can experience a loss, $s_j + \sum_{t=1}^{T} Q_{jt}p_t < \sum_{t=1}^{T} Q_{jt}P_j$ when the block bid is accepted $y_j \geq 1$. Such a block bid is called a paradoxically-accepted-block (PAB). In Europe, the first relaxation is implemented, so no bidder experiences a direct loss due to the market-clearing. The resulting market-solution will therefore generally include PRBs. The conditions (7), (9)-(11) specify the European acceptance rules. The European market clearing problem (EMCP) is defined such that a solution to the matching problem must satisfy the requirements in (7), (9)-(11).

III. Published Solution Algorithms

The two formulation presented in this section are solution algorithms presented in the literature.

A. Integrated Formulation with Linearized Complementarity Conditions (CC)

A valid bid selection is determined by (7), (9)-(11). It is possible to linearize the non-linear constraints and add these to the matching problem (1)-(6). This is similar to [15]. Restrictions (7), (9)-(11) can be linearized by noticing that they define three disjunctive states for the continuous hourly bids, and two states for binary block bids. When an hourly demand (supply) bid is totally accepted, $x_{it} = 1$ and $s_{it} \geq 0$, the bid sets an upper (lower) price bound on the hourly price p_t. When an hourly bid is partially accepted, $0 < x_{it} < 1$ and $s_{it} = 0$, the hourly price p_t must be equal to the bid price, and when the bid is not accepted, $x_{it} = 0$ and $s_{it} = 0$ the demand (supply) bid sets a lower (upper) limit on the price. These three states are modeled with two binary variables: β_{it}, which specifies whether an hourly bid is totally accepted or not and δ_{it}, which specifies whether a bid is accepted or not. This formulation requires hourly- and block-volume variables to be specified in terms of supply and demand denoted by subsets marked with respectively S and D.

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \tag{12}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \tag{13}$$
$$x_{it} \leq \delta_{it} \qquad i \in I \tag{14}$$
$$x_{it} \geq m\delta_{it} \qquad i \in I \tag{15}$$
$$x_{it} \geq \beta_{it} \qquad i \in I \tag{16}$$
$$x_{it} \leq 1 - m + \beta_{it} \qquad i \in I \tag{17}$$
$$y_j \leq 1 \qquad j \in J \tag{18}$$
$$p_t \geq P_{it}\beta_{it} \qquad i \in I^S \tag{19}$$
$$p_t \leq P_{it} + M_{it}(1-\beta_{it}) \qquad i \in I^D \tag{20}$$
$$p_t \leq P_{it} + M_{it}\beta_{it} \qquad i \in I^S \tag{21}$$
$$p_t \geq P_{it}(1-\beta_{it}) \qquad i \in I^D \tag{22}$$
$$p_t \leq P_{it} + M_{it}(1-\delta_{it}+\beta_{it}) \qquad i \in I^S \tag{23}$$
$$p_t \leq P_{it} + M_{it}(1-\delta_{it}+\beta_{it}) \qquad i \in I^D \tag{24}$$
$$p_t \geq P_{it}(\delta_{it}-\beta_{it}) \qquad i \in I^S \tag{25}$$
$$p_t \geq P_{it}(\delta_{it}-\beta_{it}) \qquad i \in I^D \tag{26}$$
$$\sum_{t=1}^{T} p_t Q_{jt} \geq y_j \sum_{t=1}^{T} P_j Q_{jt} \qquad j \in J^S \tag{27}$$
$$\sum_{t=1}^{T} p_t Q_{jt} \leq \sum_{t=1}^{T} P_j Q_{jt} + M_j(1-y_j) \qquad j \in J^D \tag{28}$$
$$x_{it} \geq 0 \qquad i \in I \tag{29}$$
$$\delta_{it}, \beta_{it} \in \{0,1\} \qquad i \in I \tag{30}$$
$$y_j \in \{0,1\} \qquad j \in J \tag{31}$$

Equations (12) and (13) specifies the objective function and balance restrictions. In (14)–(17) the relationship between the binary variables δ_{it} and β_{it} and the acceptance x_{it} is defined. The block acceptance requirement is formulated in (18). The price bounds set by the totally accepted hourly bids and totally rejected hourly bids are set by (19)–(22). In the case of a curtailed hourly bid the price must take the bid price. This is enforced by (23)–(26). Restrictions (27) and (28) enforce that no accepted block bid will experience a loss. Integer requirements are specified in (30)– (31).

B. Integrated Formulation with Strong Duality (SD)

To avoid the use of a large numbers of binary variables to express the complementarity conditions Madani and Van Vyve [7] proposes a formulation solving the EMCP taking advantage of strong duality theory. Their equivalent formulation of the CC is given below.

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \tag{32}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \qquad [p_t] \tag{33}$$
$$x_{it} \leq 1 \qquad [s_{it}] \tag{34}$$
$$y_j \leq 1 \qquad [s_j] \tag{35}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \geq \sum_{i=1}^{I}\sum_{t=1}^{T} s_{it} + \sum_{j=1}^{J} s_j \quad (36)$$

$$s_{it} + Q_{it}p_t \geq Q_{it}P_{it} \qquad [x_{it}] \quad (37)$$

$$s_j + \sum_{t=1}^{T} Q_{jt}p_t \geq \sum_{t=1}^{T} Q_{jt}P_j - M_j(1-y_j) \qquad [y_j] \quad (38)$$

$$x_{it}, s_{it}, s_j \geq 0 \quad (39)$$

$$y_j \in \{0,1\} \quad (40)$$

Equation (36) forces the objective function value to obtain a solution that satisfies optimality criteria from strong duality theory. The restrictions on the dual variables from the dual problem is specified in (37)–(38).

Duality theory is not applicable to integer problems. To see how this formulation is able to take advantage of duality theory the following proof from [7] is reproduced. The proof consists of identifying the block selections that are valid. The set of blocks J is partitioned into two subsets, the set of accepted blocks J_1 and the set of rejected blocks J_0. Upper and lower bounds on the sets of blocks can now be specified such that integer requirements are not needed, and linear programming theory holds. A block selection satisfies the European acceptance rules if $d_{j_1} = 0 \forall j_1 \in J_1$. The primal, dual and complementarity constraints for a given block partition is given below.

Primal Problem:

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \quad (41)$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \qquad [p_t] \quad (42)$$

$$x_{it} \leq 1 \qquad [s_{it}] \quad (43)$$

$$y_j \leq 1 \qquad [s_j] \quad (44)$$

$$y_{j_0} \leq 0 \qquad [d_{j_0}] \quad (45)$$

$$-y_{j_1} \leq -1 \qquad [d_{j_1}] \quad (46)$$

$$x_{it}, y_j \geq 0 \quad (47)$$

Dual Problem:

$$\min \sum_{i=1}^{I}\sum_{t=1}^{T} s_{it} + \sum_{j=1}^{J} s_j - \sum_{j_1=1}^{J_1} d_{j_1} \quad (48)$$

$$s_{it} + Q_{it}p_t \geq Q_{it}P_{it} \qquad [x_{it}] \quad (49)$$

$$s_{j_0} + d_{j_0} + \sum_{t=1}^{T} Q_{j_0 t}p_t \geq \sum_{t=1}^{T} Q_{j_0 t}P_{j_0} \qquad [y_{j_0}] \quad (50)$$

$$s_{j_1} - d_{j_1} + \sum_{t=1}^{T} Q_{j_1 t}p_t \geq \sum_{t=1}^{T} Q_{j_1 t}P_{j_1} \qquad [y_{j_1}] \quad (51)$$

$$s_{it}, s_j, d_{j_0}, d_{j_1} \geq 0 \quad (52)$$

Complementarity constraints:

$$s_{it}(1-x_{it}) = 0 \quad (53)$$

$$s_{j_0}(1-y_{j_0}) = 0 \quad (54)$$

$$s_{j_1}(1-y_{j_1}) = 0 \quad (55)$$

$$y_{j_0}d_{j_0} = 0 \quad (56)$$

$$(1-y_{j_1})d_{j_1} = 0 \quad (57)$$

$$x_{it}\left(s_{it} + Q_{it}p_t - Q_{it}P_{it}\right) = 0 \quad (58)$$

$$y_{j_0}\left(s_{j_0} + d_{j_0} + \sum_{t=1}^{T} Q_{j_0 t}p_t - \sum_{t=1}^{T} Q_{j_0 t}P_{j_0}\right) = 0 \quad (59)$$

$$y_{j_1}\left(s_{j_1} - d_{j_1} + \sum_{t=1}^{T} Q_{j_1 t}p_t - \sum_{t=1}^{T} Q_{j_1 t}P_{j_1}\right) = 0 \quad (60)$$

The proof consist of a showing that a feasible solution to the SD formulation satisfies the requirements of (41)-(60). Let $d_{j_1} = 0 \forall j_1 \in J_1$ and $d_{j_0} = M_{j_0} \forall j_0 \in J_0$. When parameters M_{j_0} and thus d_{j0} have been chosen large enough, s_{j_0} can be set to equal 0. Then (50) and (59) is satisfied. The new point $(x_{it}, y_j, p_t, s_{it}, s_{j_0}, s_{j_1}, d_{j_0}, d_{j_1})$ satisfies all constraints (41)-(60). Since primal, dual, and complementarity constraints are satisfied, the current bid selection is optimal. Also duality theory holds, so equality of the objective value of primal and dual problems holds (36). For the given values of d_{j_0} and d_{j_1} it is easy to see that $(x_{it}, y_j, p_t, s_{it}, s_{j_0}, s_{j_1}, d_{j_0}, d_{j_1})$ satisfies (32)-(40). This concludes the proof.

IV. New Algorithm

The two previous solution methods solve the market-clearing problem in a single integrated problem. To accomplish this, big M coefficients are needed to turn restrictions on and off. When the big M is included as a coefficient of a variable in the optimization problem, the big M can enter the basis matrix and make the matrix ill-conditioned. This can lead to numerical issues such that the optimal solution may not be found, or the solution time increases significantly. A general consequence of using big M coefficients in a MIP formulation is poor LP relaxation and poor upper bounding [16]. Due to these issues a formulation and solution method that does not rely on big M coefficients is preferable. In this section a new algorithm is proposed by the authors, where the matching problem and feasibility problem are solved separately in a branch-and-cut algorithm. The algorithm avoids the use of big M coefficients to specify the logic of the European acceptance rules.

Matching Problem:

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \quad (61)$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \qquad [p_t] \qquad (62)$$

$$x_{it} \leq 1 \qquad [s_{it}] \qquad (63)$$

$$y_j \leq 1 \qquad [s_j] \qquad (64)$$

$$x_{it} \geq 0 \qquad (65)$$

$$y_j \in \{0,1\} \qquad (66)$$

Feasibility Problem:

$$\min = \sum_{t=1}^{T}\left(p_t - \frac{P_t^U + P_t^L}{2}\right)^2 \qquad (67)$$

$$s_{it}\left(1 - x_{it}^*\right) = 0 \qquad (68)$$

$$x_{it}^*\left(s_{it} + Q_{it}p_t - Q_{it}P_i\right) = 0 \qquad (69)$$

$$y_j^*\left(s_j + \sum_{t=1}^{T} Q_{jt}p_t - \sum_{t=1}^{T} Q_{jt}P_i - r_j\right) = 0 \qquad (70)$$

$$s_{it}, s_j, r_j \geq 0 \qquad (71)$$

The feasibility problem consists of the complementarity conditions (68)-(70) that determine if a given bid selection found in the marching problem (x_{it}^*, y_j^*) is valid. The solution is invalid if there are PABs and $r_j > 0$. If there are no PABs, $r_j = 0$, the solution is valid. P_t^L is set to equal the last accepted hourly supply bid x_{it}^* and P_t^U is set to equal the last accepted hourly demand bid. When there is no partially accepted bid in an hour, pricing conditions for this hour is not strict, and there exists a range of prices that satisfy the pricing requirements. The price will affect how social welfare is split between producers and consumer. The objective function in the feasibility problem is specified to minimize the distance between the price p_t and the mid-point defined by the price bounds. This allows social welfare to be divided fairly among producers and consumers..A similar approach is used in Euphemia [11].

The classical branch-and-bound algorithm derives a series of upper and lower bounds on the original problem to perform an implicit enumeration of the solution set, and is commonly used to solve mixed-integer-problems (MIPs) [17]. Optimality theory from linear programming theory does not extend to integer problems, and it is necessary to use relaxation techniques to derive upper bounds on the objective function value (z). The algorithm partitions the solution set in increasingly smaller disjunctive subsets, and uses upper and lower bounds to guide the search for the optimal solution. The subsets are partitioned such that the infeasible solution is removed without cutting away any feasible solutions. If a solution to the sub-problem is feasible in the original problem, this objective function value set a lower bound (z^L). The upper and lower bounds are repeatedly updated as the algorithm progresses, and the branches in the solution tree are pruned if they cannot improve the problem bounds. The branch-and-cut algorithm extends the branch-and-bound algorithm by adding valid cuts to the sub-problems to speed up the algorithm convergence. The branch-and-cut algorithm developed in this paper used to solve the European market-clearing problem is outlined below.

1. Relaxation Both the integer requirements and the European acceptance rules are relaxed in the sub problem. The European acceptance requirements are separated in a feasibility problem, and the integer requirements (66) are relaxed. Consequently, the solution to this sub-problem may not be an integer solution, and may include paradoxically-accepted-blocks (PABs).

2. Branching Branching is executed when the solution to the sub-problem is fractional. Two new sub-problems are defined by the constraints $y_j \leq 0$ and $y_j \geq 1$ where y_j corresponds to a fractional solution variable. The fractional LP solution is thus cut away, and the solution set is partitioned into two disjunct subsets.

3. Cutting An integer solution found in the sub-problem might still include PABs. The incumbent solution is passed on to the feasibility problem. If $r_j > 0$ the

TABLE I
MARKET CLEARING RESULTS

	Day	FR1	FR2	GA1	GA2	GA3
Complimentarity Conditions (CC)	Social Welfare	721 919 204	1 100 858 295	3 525 693 736	3 579 124 037	4 007 521 063
	#Accepted Blocks	60	91	74	124	70
	Solution Time [s]	2063.4	219.69	901.42	342.08	3552.78
	#Nodes in B/B tree	155	1	1	1	1445
	#PRBs	3	0	8	0	6
Strong Duality (SD)	Social Welfare	721 919 204	1 100 858 295	3 525 693 682	3 579 124 037	4 007 521 220
	#Accepted Blocks	60	91	73	124	70
	Solution Time [s]	43.49	15.74	68.83	17.47	49.49
	#Nodes in B/B tree	244	1	532	1	1397
	#PRBs	6	1	6	0	12
New Algorithm	Social Welfare	721 919 204	1 100 858 295	3 525 693 736	3 579 124 037	4 007 521 523
	#Accepted Blocks	60	91	74	124	70
	Solution Time [s]	10.33	4.15	14.86	6.54	29.25
	#Nodes in B/B tree	103	1	196	1	440
	#PRBs	3	4	5	0	12

solution contains PABs and is infeasible in the original problem. The valid cut (73) is added to the sub-problem, which cuts away the incumbent integer solution. The current sub-problem is reoptimized and no branching is executed.

4. Pruning The sub-problem branch is pruned if, the problem is infeasible, when the sub-problem objective value is lower than the lower bound (z^L), and when the solution in the sub-problem is feasible in the original problem. A feasible solution to the original problem is obtained when the LP relaxation results in an integer solution that satisfies the European acceptance rules. If the objective function value $z > z^L$, z^L is updated

A valid cut (73) is derived from the proof in (41)-(60). For a given block selection y_j^* it is shown that duality theory relates the primal, dual, and complementarity constraints. A valid cut (36) is given by the relation between the objective function value of the primal problem and the dual problem. The solution is infeasible if $\sum_{j=0}^{J} r_j > 0$. This solution is cut away by the following inequality.

Feasibility cut

$$z_{Dual} - z_{Primal} \leq 0 \tag{72}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} s_{it}^* + \sum_{j=1}^{J} s_j^* - \left(\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_jQ_{jt}P_j\right) \leq 0 \tag{73}$$

The cut is a feasibility cut similar to that derived in Benders decomposition. The Benders decomposition isolates a set of complicating variables resulting in a considerably easier to solve sub-problem. The dual of the sub-problem is used to derive an upper bound on the master problem, and a Benders cut similar to 73 is added to the master problem. The cutting-plane approach successively builds up representations of the master problem that makes the solution to the master problem converge to an optimal solution. The dual variables included in the cut can be obtained using both the dual problem (48)-(52) and the complimentarity constraints(53)-(60). The feasibility cut (73) is obtained using the complimentarity constraints. This allows for a tighter formulation than the dual problem. The solution time of the algorithm decreases when the sub-problems in each iteration are solved more quickly. Using (53)-(60) makes it also possible to specify the objective function (67) to set correct pricing.

V. Analysis

The three market-clearing algorithms are compared using real bidding data from the French (FR) and German-Austrian (GA) bidding areas provided by EPEX SPOT. The data instances consist of a number of hard-to-clear market days with a high number of paradoxically-rejected-blocks (PRBs) spread across 2013 and 2014. The SD and CC formulations use the big M method to turn on and off restrictions. The M coefficients are initialized using the bidding data such that:

$$M_{it} = P_{max} - P_{it} \tag{74}$$

$$M_j = \sum_{t=1}^{T} P_{max}Q_{jt} - \sum_{t=1}^{T} P_jQ_{jt} \tag{75}$$

This way M is given the lowest possible value that will still make the restriction redundant when the M is invoked. Setting the solver's feasibility tolerance levels of to the lowest possible value ($1e^{-9}$) rounding errors related to the big M method will be minimized. The algorithms are run on the Xpress Optimizer version 25.01.05 on a Windows Server 2008 with 64 GB RAM and 4 AMD 12 core processors. The branch-and-cut algorithm was implemented in the following way. The standard branch-and-bound procedure in the Xpress optimizer was extended with a callback function. The callback was executed when an integer solution was found. If the solution was found infeasible a valid cut was added to the incumbent node.

The three formulations are equivalent and should find the same optimal solution. However, the SD and the CC is not able to find the optimal solution in all instances as seen in Table I. This is due to numerical issues caused by the big M entering the basis matrix, resulting in an ill-conditioned basis. The SD is not able to find the optimal solution for two of the five data instances, while the CC does not find the optimal solution in one out of five instances. Even though the CC performs better than the SD for these instances, the solution time increases. The solver uses considerable time adding a number of valid cuts. This is seen to shorten the branch-and-bound procedure by reducing the number of nodes for most days. The time spent adding these cuts outweigh the gains.

The deviation in social welfare when the optimal solution is not found is small, see Table I. The major problem, however, is that the change in basis commits the wrong set of generators. This means that a number of generators that should be accepted is rejected. Confidence in the market's ability to provide a fair outcome is essential for market participation. In cases where the SD and the CC finds the optimal solution, the new algorithm is able to find the optimal solution up to 4 times faster than the SD and up to 200 times faster than the CC.

The SD and the CC also have issues with undetermined pricing. For the hours in which no hourly bid is curtailed, the program is free to set any price within the price bounds. Changing the price will not change the economical surplus, but the distribution of this surplus between consumers and producers is affected. Consequentially, the price should be set to distribute the surplus appropriately among producers and consumers. This can only be accomplished by separating the market-clearing problem in a matching problem and a feasibility problem as is done in the new algorithm. When pricing is not fixed, a number of block solutions might exist that satisfy optimality criteria. This is the reason even though the SD and the CC finds the optimal solution, a different number of blocks are paradoxically rejected (PRB) (ref Table I).

VI. Discussion

Madani presents a Benders decomposition of the SD formulation [7]. It is found that the Benders decomposition is able to solve problem instances much faster, but that the SD formulation is able to solve a larger number of instances to optimality [7]. This paper has pointed out two weaknesses with the SD formulation that the new algorithm developed in this paper is able to solve. For especially hard-to-solve problem instances with a high number of PRBs (GA1 and GA3), the SD formulation is not able to find the optimal value. The branch-and-cut algorithm in this paper is able to solve these instances to optimality and at the same time considerably faster. The second issue with the SD formulation is that it is not able to set correct pricing when pricing is indeterminate. The result is that even though the optimal solution is found, the set of blocks that are PRBs is not uniquely determined. These free variables will be set to their lower limit by the optimizers built-in default settings. Consequently, there is no decision rule that specifies whether a block will be paradoxically rejected or not among a number of sets of potential PRBs for an undetermined solution. The solution method in this paper allows the set of PRBs to be uniquely determined in the feasibility problem.

VII. Conclusion

This paper has revealed weaknesses with formulations of the day-ahead market clearing problem presented in the literature. Formulations based on the big M approach will have numerically unstable solutions. The authors propose a new formulation based on a branch-and-cut method avoiding the big M approach. This formulation solves all market instances significantly more efficient than the two alternate formulations analyzed. With the proposed algorithm all solutions are found within two minutes. The algorithm allows splitting economical surplus fairly among market participants by setting market prices dividing the surplus after a predefined ratio in cases where prices are not set by curtailed bids. The resulting algorithm is thus a more stable, fair, and fast algorithm than previously established algorithms for the European market-clearing problem. For a reliable and fast market-clearing algorithm, European power exchanges should use the algorithm proposed in this paper.

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Increasing the Efficiency of the European Day-Ahead Power Market using Exclusive Block Groups and Flexible Volume Blocks

Carl Fredrik Tjeransen, Erik B. Rudlang

***Abstract*—The recent increase in intermittent generation from renewable energy sources (RES) has resulted in increased price volatility and complexity of the decentralized bidding problem. This paper analyzes the value of block products in the market, and argues that there is a mismatch between the products offered on the European power exchanges and the market participants needs. Two new types of block products are analyzed, exclusive block groups, recently introduced at European power exchanges, and flexible volume blocks, proposed by the authors. Exclusive block groups and flexible volume blocks can be used to signal flexibility in operations to the market operator. The two products will allow market participants to better communicate their needs to the market. The two bidding strategies are evaluated based on real market data from EPEX SPOT. The results show that under volatile market conditions flexible products are able to transmit valuable information and increase market efficiency and moderate price volatility. The accepted volume from block bids increases as much as 911 % and the market efficiency increases up to 10 % when power producers use these two bidding strategies. The main contribution of this paper is the evaluation of exclusive block groups' and flexible volume blocks' ability to ensure a well functioning market under the high influence of RES in Europe**

***Index Terms*—Electricity market design, power system economics, market research, thermal power production**

NOMENCLATURE

Sets

I	Set of hourly bids
J	Set of block bids
K	Set of exclusive groups
T	Set of time-steps

Indices

i	Index of hourly bids
j	Index of block bids
k	Index of exclusive groups
t	Index of time-steps

The authors are with Norwegian University of Science and Technology (NTNU), Trondheim, Norway, (e-mail: cftjeransen@hotmail.com, erudlang@gmail.com)

Variables

x_{it}	Acceptance of hourly bid i in time-step t
y_j	Binary variable; 1 if block bid j is accepted, else 0
y_{kj}	Binary variable; 1 if block bid j in exclusive group k is accepted, else 0
q_{kjt}	Acceptance of flexible block bid j in time-step t in exclusive group k
s_{it}	Dual variable on the upper bound of x_{it}
s_j	Dual variable on the upper bound of y_j
s_{kj}	Dual variable on the upper bound of y_{kj}
p_t	Market price in time-step t
r_j	Slack variable on the acceptance bound of block bid j
r_{kj}	Slack variable on the acceptance bound of block bid j in exclusive group k

Parameters

Q_{it}	Hourly bid volume for bid i in time-step t
Q_{jt}	Block bid volume for bid j in time-step t
Q_{kjt}	Block bid volume for bid j in exclusive group k in time-step t
Q_{kjt}^{max}	Max block bid volume for flexible bid j in exclusive group k in time-step t
Q_{kjt}^{min}	Min block bid volume for flexible bid j in exclusive group k in time-step t
P_{it}	Hourly bid price for bid i in time-step t
P_j	Block bid price for bid j
P_{kj}	Block bid price for bid j in exclusive group k
P_t^U	Upper price limit on p_t
P_t^L	Lower price limit on p_t

I. INTRODUCTION

THE SHARE of Renewable Energy Sources (RES) in the power mix is rapidly increasing around the world [1]. Large scale integration of RES leads to more volatile energy prices due to the intermittent nature of especially wind and solar energy [2]–[4]. This intensifies the need for a good market design considering the market structure [5], [6]. Several solutions have been proposed in the literature to meet these changes, for instance the use of stochastic information in the unit commitment [7], [8]. This paper will consider the impact on the day-ahead market design, and propose policy changes to meet the new reality.

There are two main designs of the day-ahead market: The pool model, used in a number of states in the U.S., and the power exchange model used by most European countries. The main difference being, unit commitment decisions are fully decentralized in the European model, whereas these decisions are made centrally by the system operator in the U.S. Power exchanges will inevitably suffer from some efficiency losses due to lack of resource coordination [10], [11] when unit commitment is decentralized. This is the consequence of market participants individually maximizing their own profits.

The European day-ahead market is organized as a single financially binding auction. Each participant must individually find bids that best reflect optimal unit commitments. Determining optimal bids based on marginal cost curves has been the topic for extensive research [12]–[15]. Some units have high start-up costs and/or technical restrictions such as ramping and run-time restrictions. Conventional power producers are left with the challenging task to convey the non-convex properties of their power generation to the market. Hourly marginal cost curves may result in infeasible commitments that do not cover start-up costs [6]. Block bids are introduced to signal these non-convex properties to the market. A block bid consist of a single price-quantity for a number of hours that is either totally accepted or totally rejected.

Increased market volatility makes planning ahead significantly harder for power producers and the need to signal flexibility becomes crucial. It may no longer be possible to run generators at the most efficient point for long continuous periods of time which used to be the standard for such power plants [7]. The data in [9] show that thermal power produces have significant operational flexibility. The "fill-or-kill" acceptance of block bids is too rigid to signal the operational ability. Market efficiency would improve if generators were able provide the market with this information. New bid products that can include this flexibility should therefore be considered.

Block bids in exclusive groups can be used to signal technical and economical flexibility. This product was introduced by some European power exchanges February 4, 2014 [16], [17]. A power producer may have several different dispatch profiles fulfilling the plants technical and economical restrictions. Exclusive groups enable power producers to specify a group of blocks where at most one block is accepted. It is thus possible to submit bids with different production profiles and increase the chances of acceptance.

This paper proposes a new product, flexible block bids, which will give producers a new way to signal flexibility. This block order is specified by a minimum and maximum volume for each hour of the block, and a price. The bid should be specified such that at minimum block volumes the price will satisfy the bidders' revenue adequacy. For each hour the bidder may receive a unique commitment between the upper and lower limit, thus relaxing the "fill-or-kill" nature of standard block bids.

This article is to the best of the authors' knowledge the first to evaluate exclusive block groups. The paper also contributes by proposing a new bid product, flexible volume blocks, that enable power producers to signal additional characteristics to the market. Real market data from EPEX SPOT is used to benchmark these products. The results show that both products will increase market efficiency. The new available flexibility leads to greater acceptance and volumes from block bids. Accepted supply volume from block bids increases with up to 911 %, and market efficiency increases as much as 10 %.

II. Operational flexibility and a restrictive power exchange

Thermal power production amount to a large share of power generation in many European power markets [18]. Preparing bids in the day-ahead market for thermal power plants is complicated due to two factors. First, the plants have a number of technical restrictions. In Table I five different units and some of their technical properties are shown. There are limits on ramping and run-time for the turbines. Second, to start a thermal generator is a costly procedure, especially for lignite

TABLE I
GENERATOR THERMAL PROPERTIES [9]

Unit	Power: [MW]		MaxRamp	Time from stop to:		Minimum time: [h]	
	Max	Min	[MW/min]	Warm [h]	Cold [h]	Start-Stop	Stop-Start
1	274	160	2	5	12	8	4
2	342	180	2	5	12	8	4
3	378	200	24	5	12	4	3
4	476	250	24	5	12	4	3
5	152	63	8	5	12	1	1

TABLE II
GENERATOR COSTS [9]

Unit	Type	Marginal Cost	Commitment Cost	Start Cost [EUR]		
		[EUR/MWh]	[EUR/h]	Hot	Warm	Cold
1	lignite	29	1894	46600	64007	87217
2	lignite	31	1644	58165	79892	108862
3	CCGT	55	3367	16012	24832	42472
4	CCGT	55	3839	19766	30476	51896
5	OCGT	85	965	2568	2568	2568

plants (Table II). These start-up costs are defined by the units' thermal state (Table I).

The power generators must each day make decisions on optimal market commitments for their units. Power producers can use block products to ensure that technical constraints such as minimum run-time and ramping constraints are met. Block bidding also allows the cost of starting up the generator to be more accurately reflected by spreading the cost over a number of hours. However, the traditional block bid's "fill-or-kill" nature makes it hard to signal alternative production profiles since each block bid may result in a commitment. A large number of alternative operating profiles may exist for a generator that is impossible to signal using simple' block bids.

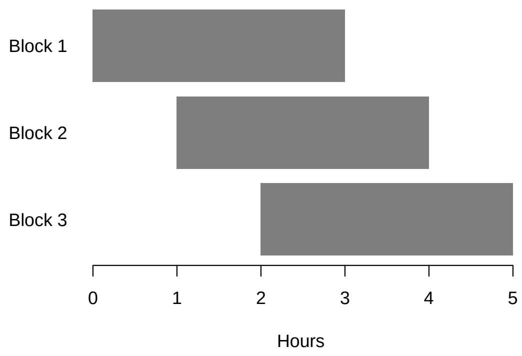

Fig. 1. Illustration of how exclusive block groups can be constructed by combining three blocks with different start-up times.

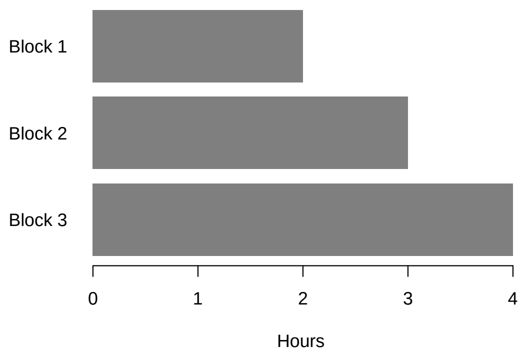

Fig. 2. Illustration of how exclusive block groups can be constructed by combining three blocks of different lengths.

A recent development in the electricity trading on European power exchanges is the newly introduced product, exclusive block groups. This product allows the power producers to signal a set of discrete operating profiles, while the market clearing selects the profile that contributes most to social welfare. This is a useful product that can signal alternative start-up times and alternative production lengths. These two operating characteristics are illustrated in Fig 1 and 2. There are other technical characteristics of thermal power production that are impossible to signal due to the discrete nature of exclusive block groups. Table I shows typical operating characteristics for a set of thermal power generating technologies. Most of these generators are able to ramp from minimum to maximum power within a single hour. Simple blocks either stand-alone or organized as an exclusive block group consists of fixed volumes for each time step. Power producers are therefore not able to signal this ramping flexibility.

A new product, flexible volume blocks, is proposed by the authors to enable thermal power producers to signal this flexibility. A flexible volume block bid consist of minimum and maximum production volume each hour and a block price as seen in Fig. 3. This product will enable power producer to signal ramping flexibility as a stand-alone block or as included in exclusive block groups. In the next section we extend the formulation in [19] to construct a market-clearing algorithm that can handle exclusive block groups and flexible volume blocks.

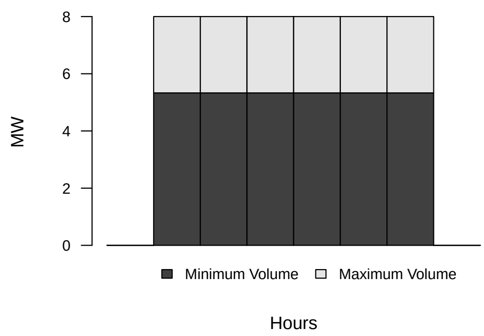

Fig. 3. Example of a flexible volume block with minimum and maximum production volumes. The difference between these two volumes reflects the unit's ramping capability. If accepted, the commitment can be any volume between the limits in each hour.

III. FORMULATION

There are no published algorithm formulations for the European market-clearing problem with exclusive block groups or flexible volume blocks. In this section two formulations are developed that can be used to clear the day-ahead market with exclusive block groups and flexible volume block groups. The market clearing problem is solved using the branch-and-cut algorithm presented in [19]. Solving the market clearing is complicated due to the non-convex properties of the problem induced by binary variables modeling "fill-or-kill" acceptance of block bids. The non-convex nature of the market makes the existence of linear prices that clears the market generally impossible. To be able to clear the market a set of European acceptance rules are specified [20]. A supply (demand) block bid is "in-the-money" if the volume weighted market price is below (above) the block bid price. A supply (demand) block is "out-of-the-money" if the volume weighted market price is above (below) the block bid price. Due to the rigid structure of the block bids, linear prices will results in either excess supply or excess demand. Consequently, to allow the market to clear some blocks that are "in-the-money" must be rejected (paradoxically rejected blocks), or some blocks that are "out-of-the-money" must be accepted (paradoxically accepted blocks). The European acceptance rules allow paradoxically rejected blocks (PRBs), so that no market participants will suffer a direct loss due to the clearing. This means that some block bids might not be accepted even though the bid is profitable. However, no paradoxically accepted blocks (PABs) are allowed.

The solution method uses a branch-and-cut algorithm where valid cuts are added to speed up the convergence of the combinatorial problem. When an integer solution is found in the branch-and-bound tree, this solution is evaluated in the sub-problem. If the block selection contains PABs, a valid cut is added to the resulting sub tree. When the incumbent solution satisfy the acceptance rules, a feasible solution is found.

A. Baseline

Master Problem:

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \tag{1}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} = 0 \qquad [p_t\,] \tag{2}$$

$$x_{it} \leq 1 \qquad [s_{it}] \tag{3}$$

$$y_j \ \leq 1 \qquad [s_j\,] \tag{4}$$

$$x_{it} \geq 0 \tag{5}$$

$$y_j \in \{0, 1\} \tag{6}$$

Q_{it} and Q_{jt} are defined such that supply bid are negative and demand bids are positive. The objective function (1) in the master problem maximizes the social welfare. Equation (2) ensures the balance of demand and supply in each hour, while (3) and (4) sets the upper limit on the bid quantities. Each incumbent solution marked by * is passed on to the sub-problem where P_t^U is set to the bid price of the last accepted demand bid and P_t^L is set to the bid price of the last accepted supply bid.

Sub-Problem:

$$\min = \sum_{t=1}^{T}\left(p_t - \frac{P_t^U + P_t^L}{2}\right)^2 \tag{7}$$

$$s_{it}(1 - x_{it}^*) = 0 \tag{8}$$

$$x_{it}^*\left(s_{it} + \sum_{t=1}^{T} Q_{it}p_t - \sum_{t=1}^{T} Q_{it}P_i\right) = 0 \tag{9}$$

$$y_j^*\left(s_j \ + \sum_{t=1}^{T} Q_{jt}p_t - \sum_{t=1}^{T} Q_{jt}P_j - r_j\right) = 0 \tag{10}$$

$$s_{it}, s_j, r_j \geq 0 \tag{11}$$

The sub-problem specifies the acceptance rules. Equations (8) and (9) require that all profitable hourly bids must be accepted and that all non-profitable bids must be rejected. Restriction (10) enforce the block acceptance. Only profitable block bids are allowed. If the incumbent solutions contains PABs, the solution is cut away using the valid cut (12).

$$\sum_{i=1}^{I}\sum_{t=1}^{T} s_{it}^* + \sum_{j=1}^{J} s_j* \leq \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{j=1}^{J}\sum_{t=1}^{T} y_j Q_{jt} P_j \tag{12}$$

When an hourly bid is curtailed, the price p_t will be uniquely determined. However, when there are no curtailed bids, the price p_t will be undetermined. The objective function is specified such that the price is set to minimize the distance between the price p_t and the upper and lower price bounds. The price will determine how the social welfare is split between the producers and consumers. Minimizing the distance from the price to the midpoint ensures that the surplus is equally divided among producers and consumers, when the price is not uniquely determined.

B. Exclusive Block Groups

In this section the baseline formulation from Section III-A is extended to support exclusive groups. An additional index k is included representing the exclusive block groups in the model.

Master Problem:

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} y_{kj} Q_{kjt} P_{kj} \tag{13}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} y_{kj} Q_{kjt} = 0 \qquad [p_t\,] \tag{14}$$

$$x_{it} \leq 1 \qquad [s_{it}\,] \tag{15}$$

$$y_{kj} \ \leq 1 \qquad [s_{kj}] \tag{16}$$

$$\sum_{k=1}^{K} y_{kj} \leq 1 \tag{17}$$

$$x_{it} \geq 0 \tag{18}$$

$$y_{kj} \in \{0, 1\} \tag{19}$$

At most one block in a group can be accepted. This is specified by (17).

Sub-Problem:

$$\min = \sum_{t=1}^{T}\left(p_t - \frac{P_t^U + P_t^L}{2}\right)^2 \tag{20}$$

$$s_{it}(1 - x_{it}^*) = 0 \tag{21}$$

$$x_{it}^*\left(s_{it} + \sum_{t=1}^{T} Q_{it}p_t - \sum_{t=1}^{T} Q_{it}P_i\right) = 0 \tag{22}$$

$$y_{kj}^*\left(s_{kj} \ + \sum_{t=1}^{T} Q_{kjt}p_t - \sum_{t=1}^{T} Q_{kjt}P_{kj} - r_{kj}\right) = 0 \tag{23}$$

$$s_{it}, s_{kj}, r_{kj} \geq 0 \tag{24}$$

The sub-problem and the cut (12) is extended to include exclusive groups.

C. Flexible Block Bids

To incorporate flexible volume blocks in the exclusive block group formulation in Section III-B the fill-or-kill restriction on blocks is partially relaxed. The volumes of the block are allowed to vary within an upper and lower limit if accepted. This is modeled by introducing an additional flexible block volume acceptance variable q_{kjt} specifying how large proportion of the maximum block volume is accepted in each hour.

Master Problem:

$$\max \sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it}P_{it} + \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} q_{kjt}Q_{kjt}^{max}P_{kj} \tag{25}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{it}Q_{it} + \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} q_{kjt}Q_{kjt}^{max} = 0 \quad [p_t\ ] \tag{26}$$

$$x_{it} \leq 1 \quad [s_{it}] \tag{27}$$

$$y_{kj} \leq 1 \quad [s_{kj}] \tag{28}$$

$$\sum_{k=1}^{K} y_{kj} \leq 1 \tag{29}$$

$$q_{kjt} \leq y_{kj} \tag{30}$$

$$q_{kjt} \geq \left(\frac{Q_{kjt}^{max} - Q_{kjt}^{min}}{Q_{kjt}^{max}}\right) y_{kj} \tag{31}$$

$$x_{it} \geq 0 \tag{32}$$

$$y_{kj} \in \{0, 1\} \tag{33}$$

Equations (30) and (31) are added relating the block volume acceptance variables q_{kjt} to the binary block acceptance variables y_{kj}.

Sub-Problem:

$$\min = \sum_{t=1}^{T}\left(p_t - \frac{P_t^U + P_t^L}{2}\right)^2 \tag{34}$$

$$s_{it}(1 - x_{it}^*) = 0 \tag{35}$$

$$x_{it}^*\left(s_{it} + \sum_{t=1}^{T} Q_{it}p_t - \sum_{t=1}^{T} Q_{it}P_i\right) = 0 \tag{36}$$

$$y_{kj}^*\Bigg(s_{kj} + \sum_{t=1}^{T} q_{kjt}^* Q_{kjt}^{max} p_t - \sum_{t=1}^{T} q_{kjt}^* Q_{kjt}^{max} P_{kj} - r_{kj}\Bigg) = 0 \tag{37}$$

$$s_{it}, s_{kj}, r_{kj} \geq 0 \tag{38}$$

In the sub-problem, the non-negative surplus restriction (37) is now modified to adjust for variable block volumes.

IV. Analysis

This section analyzes the efficiency gains that can be made when exclusive block groups and flexible volume blocks are introduced to the market. This analysis is based on five days of actual bidding data between March 2013 and January 2014 from the French bidding area (FR) and the German-Austrian bidding area (GA) provided by EPEX SPOT. Since the data does not include exclusive block groups and flexible volume blocks three assumptions are made to construct these bid types. First, each block bid corresponds to a separate generator. Second, there are no restrictions in the extension in time of the production from a generator, or the start-up time of a generator. Third, the generator is assumed to have ramping flexibility similar to the generating technologies in Table I. Less flexible generation sources such as baseload generation from coal and lignite have long run-time requirements and will have to be included as a block with a long duration. More flexible sources such as combined cycle gas turbines (CCGT) and open cycle gas turbines (OCGT) plants have shorter run-time requirements. A linear relation between the original length of the block and the ramping flexibility is assumed to model this effect where maximum flexibility of 50 % is set for 2 hour long block bids, and minimum flexibility of 33 % is set for 16 hour long blocks. Table I shows that most of the generators have a ramping flexibility close to 100 %. The implementation is therefore based on a conservative estimate of this flexibility.

A non-profiled block is defined as a simple block with equal volumes in all hours of the block. Exclusive block groups are created based on the non-profiled blocks in the data set. For every non-profiled supply block an exclusive group was made that consisted of all possible start-up times and lengthened combinations of the original block as seen in Fig. 1 and 2. In the most extreme case an exclusive group consists of 300 blocks with different start-up times and lengths. The non-profiled blocks were selected to ease the construction of the new data set, and because these blocks are assumed to originate from the more flexible generators as they have no ramping requirements at start/stop.

To analyze the effect of introducing flexible volume blocks, the same non-profiled supply blocks are used to construct flexible volume blocks. The flexible volume block consists of a minimum volume and a maximum volume reflecting the ramping flexibility of the generator (Fig 3). The minimum volume is set according to the assumed relation between original block length and ramping flexibility. The block was constructed to satisfy minimum revenue requirement of the block which is assumed to correspond with the original volume and price of the block. The price of the block was held fixed. Consequently, when the minimum volumes replace maximum volumes, the block must be extended to additional hours to satisfy the minimum revenue requirement, as seen in Fig. 4. The blocks were also combined in exclusive block groups with different start up times, and different lengths. It is thus possible to analyze the isolated effect of adding ramping flexibility.

The result of including exclusive groups is shown in Table III. When the decisions on when to start and how long to run are left to the market-clearing algorithm, a larger part of the

TABLE III
VALUE OF EXCLUSIVE GROUPS COMPARED WITH BASELINE

Case \ Day	**FR1**	**FR2**	**GA1**	**GA2**	**GA3**
Number of Supply Blocks Accepted					
Normal Blocks	43	47	48	29	26
Exclusive Groups	55	74	54	56	30
Increase	28 %	57 %	13 %	93 %	15 %
Supply Block Volume Accepted [MWh]					
Normal Blocks	18 617.8	9 624.6	28 857.4	41 799.3	16 815.4
Exclusive Groups	45 453.1	47 345.2	54 752.0	77 883.7	40 580.0
Increase	144 %	392 %	90 %	86 %	141 %
Social welfare [EUR]					
Normal	721 919 204	1 100 858 295	3 525 693 736	3 579 124 037	4 007 521 523
Exclusive Groups	795 286 327	1 181 844 013	3 526 158 038	3 579 480 904	4 007 921 023
Increased value	73 367 123	80 985 718	464 302	356 867	399 500
Increase	10.163 %	7.357 %	0.013 %	0.010 %	0.010 %
Solution times [s]					
Normal	10.33	4.15	14.86	6.54	29.25
Exclusive Groups	197.58	204.35	54.81	224.7	113.74

TABLE IV
VALUE OF FLEXIBLE VOLUME BLOCKS COMPARED WITH BASELINE

Case \ Day	**FR1**	**FR2**	**GA1**	**GA2**	**GA3**
Number of Supply Blocks Accepted					
Original Blocks	43	47	48	29	26
Flexible Volume Blocks	54	144	54	42	29
Increase	26 %	206 %	13 %	45 %	12 %
Supply Block Volume Accepted [MWh]					
Original Blocks	18 617.8	9 624.6	28 857.4	41 799.3	16 815.4
Flexible Volume Blocks	45 802.4	97 313.4	60 493.4	78 607.4	89 888.0
Increase	146 %	911 %	110 %	88 %	435 %
Social welfare [EUR]					
Original Blocks	721 919 204	1 100 858 295	3 525 693 736	3 579 124 037	4 007 521 523
Flexible Volume Blocks	795 300 685	1 181 844 004	3 526 158 118	3 579 511 076	4 007 919 772
Increased value	73 381 481	80 985 709	464 382	387 039	398 249
Increase	10.165 %	7.357 %	0.013 %	0.011 %	0.010 %
Solution times [s]					
Original Blocks	10.33	4.15	14.86	6.54	29.25
Flexible Volume Blocks	6037.03	6234.00	3432.51	6327.76	5406.66

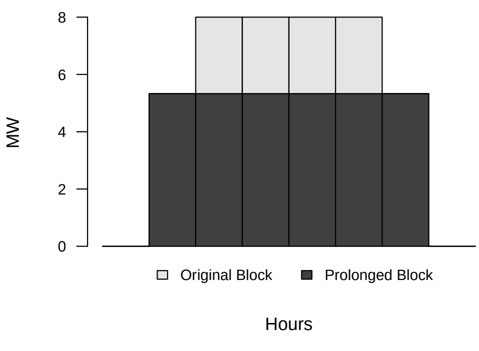

Fig. 4. Implementation of flexible volume blocks. The total volume and price of both blocks are equal. Revenue adequacy is therefore satisfied.

unit commitment problem is solved centrally. The results show that accepted supply volume increases as much as 392 % in FR and 141 % in GA. When better unit commitment decisions are made, social welfare increases by 10.163 % in FR and 0.013 % in GA. Since thermal power production is more competitive in the FR market than the GA market, social welfare increases more dramatically in this market.

The effect of introducing flexible volume blocks is shown in Table IV. The results show that when ramping flexibility is signaled to the market, volumes from block bids increases up to 911 % in FR and 435 % in GA. For all days accepted block volumes increases compared to exclusive block groups. Even though volumes increase for all days, the number of blocks accepted decrease some days (FR1, GA2, GA3). This gives the important insight that some blocks bids corresponding to certain generation technology are more competitive. When ramping flexibility is signaled, these generators are able to improve their competitiveness in the market. When the most competitive generators are able to serve a larger share of demand, market efficiency increases.

Ramping flexibility will not affect market efficiency significantly, but it will allow the most competitive sources to account for a larger share of production. The market-clearing will thus be more competitive and the surplus in the market will be distributed more fairly. Market efficiency can be seen to increase slightly for the days with the highest price volatility such as FR1 and GA2. The data from EPEX SPOT show moderate price volatility. It is therefore expected that the value of flexible volume blocks in terms of market efficiency will be even greater for days with higher price volatility.

Including flexible volume blocks the solution time increases dramatically. Reducing the size of the exclusive groups improves the solution time, and the number of flexible volume blocks would have to be limited if power exchanges were to be able to clear the market in sufficient time. Preprocessing the data and problem-specific heuristics to find feasible lower bounds would probably be a good starting point to improve the solution time.

Flexible volume blocks and exclusive block groups increases market efficiency and allow prices to more closely reflect competitive market prices. Fig. 5 shows how the rigidness of the traditional blocks affects the price signal and that the block structure distorts the price signal and makes prices unnecessary volatile. Exclusive block groups and flexible volume blocks reduce price volatility by better utilizing the resources in the market. The day-ahead market prices provide valuable information in additional markets, such as the financial forward market and bilateral power markets. Incorrect pricing will therefore not only affect the participants in the auction, but provide inaccurate signals to the wider electricity community.

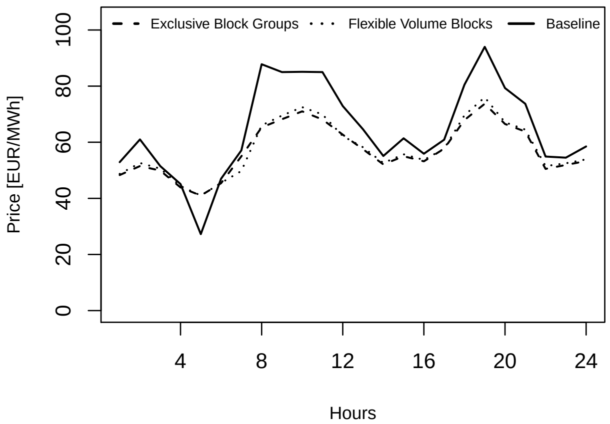

Fig. 5. Illustration on how market prices are set in the three different cases for FR2. Exclusive block groups and flexible volume blocks reduces prices volatility. This is due to the additional flexibility signaled to the market.

V. Discussion

A number of assumptions were made to perform the analysis in Section IV. Some of these might not be accurate. First, some of the blocks might originate from the same generator and the modification done would then result in infeasible commitments. Second, there might be limitations in the start-up of a generator due to external obligations. Third, the exact ramping flexibility is not known and these might not accurately reflect the flexibility in the portfolio of generators in the market. This paper does not aspire to perfectly model the market situation, rather to perform initial analyses on the potential effect of these products in the market. The assumptions made provide the necessary means to evaluate this potential.

This paper adds to the literature that evaluates the role of the market operator in making economic decisions on behalf of the market participants. Exclusive block groups and flexible volume blocks strengthen the role of the market operator in making economic decisions on behalf of the market participants. Market participants signal a larger share of operating characteristics to the market operator through exclusive block groups and flexible volume blocks. Transferring some decision-making centrally is seen to increase volumes from blocks bids and increase market efficiency. The development in this paper can be seen as a step towards a hybrid market design, taking advantage of strengths from both the pool and the power exchange.

There is a trade-off when decision-making is shifted to the market operator. The market operator clears the market to maximize social welfare. The dispatch might not be incentive compatible, as the bidder wants to maximize individual profit. The market commitment may result in what has been termed a profit suboptimal solution [21], [22]. In a pool context this raises fairness issues since market participation is mandatory. When exclusive block products and flexible volume blocks are submitted voluntarily to a power exchange it is because they believe these products are able to provide better returns in the market

VI. Conclusion

Increased penetration of renewables in the European market has revealed weaknesses in the design of the day-ahead market. Unstable prices increases the complexity of the decentralized bidding problem and the result is poor unit commitment decisions. Consequently there is a value in signaling alternative production profiles. This cannot be signaled with traditional block bid, however, exclusive block groups and flexible volume blocks can effectively transmit this information to the market. The effect of these products is analyzed based on real market data from EPEX SPOT. The results show that exclusive block groups and flexible volume blocks are able to increase the market efficiency and make the day-ahead market less volatile. As more countries transition to a green power system, the importance of a well-designed market where both conventional and renewable energy sources can coexist increases. This paper provides some insight into the design of a market that facilitates this transition.

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