FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Modeling the Iberian Market Clearing Procedure based on EUPHEMIA

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Resumo

O algoritmo EUPHEMIA surgiu da vontade de sete *Power Exchanges* em criar o projeto *Price Coupling of Regions* que visa unificar o mercado de eletricidade na Europa. A unificação do mercado Europeu permite que as transações de energia ocorram de maneira menos restrita, uma vez que deixam de ser limitadas por âmbito territorial. Este algoritmo, visto ser bastante robusto, considera todos os diferentes tipos de ofertas que podem diferir nos mercados regionais Europeus e tem em conta as interligações entre mercados.

Desta forma, evita o congestionamento nas interligações de forma a que não haja *Market Splitting* e contribui para uma maior homogeneização dos preços de eletricidade nos países que participam na iniciativa, trazendo ainda uma maior transparência nas transações.

Tendo o EUPHEMIA como base, esta dissertação foca-se na construção de um modelo simplificado do algoritmo em questão capaz de modelar o mercado diário do MIBEL tendo em conta as propostas simples e complexas, que são usadas no mercado Ibérico, assim como as suas restrições. Por conseguinte, é possível fazer uma análise das consequências da introdução deste tipo de propostas no algoritmo de otimização e calcular o preço de mercado bem como a quantidade de energia a ser transacionada.

Abstract

The EUPHEMIA algorithm emerged from the will of seven Power Exchanges to create the Price Coupling of Regions project, which aims at unifying the European electricity market. The unification of the European market allows for energy transactions to take place in a less restricted manner, since they are no longer restricted by territorial scope. This algorithm, since it is quite robust, considers all different types of orders from all the European regional markets and takes into account interconnections between markets.

Therefore, it avoids congestion in the interconnections so that Market Splitting is prevented and contributes to a greater homogenization of electricity prices in the countries that participate in the initiative, which also leads to greater transparency in transactions.

Having EUPHEMIA as a base, this dissertation focuses on the construction of a simplified model of the algorithm, capable of modeling the day-ahead market of MIBEL taking into account simple hourly and complex orders that are used in the Iberian market, as well as its constraints. It is possible then, to analyze the consequences of introducing this type of orders in the optimization algorithm and to calculate the Market Clearing Price as well as the traded energy.

Key words: Day-Ahead Market, EUPHEMIA, MIBEL, Power exchange, Single European Market Coupling.

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Catarina Isabel Nunes Soares

"Simplicity is the ultimate form of sophistication"

Leonardo Da Vinci

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List of Acronyms and Symbols

AGC	Automatic Generation Control System
ATC	Available Transfer Capacity
EUPHEMIA	Pan-European Hybrid Electricity Market Integration Algorithm
FB	Flow Based
GME	*Gestore dei Mercati Energetici*
LGC	Load Gradient Condition
MCP	Market Clearing Price
MCQ	Market Clearing Quantity
MIBEL	*Mercado Ibérico de Eletricidade*
MIC	Minimum Income Condition
MIQP	Mixed Integer Quadratic Program
NTC	Net Transfer Capacity
OMIE	*Operador del Mercado Ibérico de Energía* - Spanish Polo
OMIP	*Operador do Mercado Ibérico de Energia* - Portuguese Polo
OPCOM	*Operatorul Pietei de Energie Electrica si de gaze naturale din România*
OPEC	Organization of Petroleum Exporting Countries
PCR	Price Coupling of Regions
PRB	Paradoxically Accepted Block
PRMIC	Paradoxically Accepted Minimum Income Condition
PTDF	Power Transfer Distribution Factor
PUN	*Prezzo Unico Nazionalle*
PX	Power Exchange
RAM	Remaining Available Margin
RNT	*Rete di Trasmissione Nazionale*
SSC	Scheduled Stop Condition
SWF	Social Welfare Function
TGE	*Towarowa Gielda Energii*
TRM	Transfer Reliability Margin
TSO	Transmission System Operator
TTC	Total Transfer Capacity

Chapter 1

Introduction

This chapter presents a brief overview about the problem in hand. Firstly, the context and motivation for the development of this thesis will be discussed, mentioning the importance and need for the integration of the Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA) in the market coupling procedure. From then on, the objectives and purpose of the project will be addressed as well as the structure and organization of the present document.

1.1 Context and Motivation

The electric power system is designed to supply electric power in order to cover demand of electricity with quality in the most secure and optimal way possible. An electrical power system can be broadly divided into generators, that supply power, the transmission system that leads the power from the generating units, such as power plants to an electrical substation, and the distribution system that feeds the power to nearby homes and industries [1]. It is, therefore, a subject of greater importance that deserves attention, since human life is very dependent on its existence.

Since its creation until the present day, the electricity sector has suffered many structural changes and an increase in complexity was noticeable, especially when the deregulation process began.

A change of paradigm and an increase in complexity was noticeable when dispersed generation was introduced in the electrical network, encouraging the use of renewable energy sources in a supporting of a growing environmental awareness. This type of production is usually connected to the distribution system, includes generators with relatively low capacity and is not centrally planned or dispatched [1].

Generally, in Europe, there are day-ahead and intraday markets, where participants can freely set their bids and the price calculation in the wholesale electricity markets is carried out by the Power Exchanges (PXs) [2].

The next step is to integrate these markets and transition to a Pan-European Electricity Market, which is a challenging process if the regional markets are too diverse, since a lot of negotiations are needed to establish a single electricity market in Europe [3].

For this purpose, seven PXs (OMIE, Nord Pool, EPEX SPOT, GME, OPCOM, OTE and TGE) created a project called Price Coupling of Regions (PCR), that aims at developing a single price coupling solution to calculate day-ahead electricity prices across Europe [3].

One of the main features of the PCR project was to develop an algorithm, the EUPHEMIA, to be used by all the PXs involved, in order to solve the day-ahead market, giving more stability and transparency to the process [3].

Hence, there is a growing interest in analyzing EUPHEMIA, because it is something rather recent fully operating only since February 2015. Being useful for market participants to gain experience and knowledge to better understand how they should behave and benefit from the algorithm and the market integration.

1.2 Objectives

The main goal of this work is to solve the market clearing procedure for the day-ahead market in *Mercado Ibérico de Eletricidade* (MIBEL) using a simplified model based on the rules and procedures of EUPHEMIA.

Such model must support data used in the Iberian Market as its inputs, which are mainly simple hourly orders and complex orders from all market players in both Portugal and Spain. It also must take into account the restrictions associated with the orders and the market constraints. Moreover, in order to solve the day-ahead market problem, it has to compute market clearing prices and market clearing quantities for each hour of a given day.

After having a functional simplified model, it is possible to evaluate the effect of the applied constraints on the calculation of prices in the day-ahead market. Thereby, to achieve this, the work was divided into four major steps, each one containing several tasks.

First, it was necessary to study all the necessary background for the implementation and to understand the concept behind the algorithm. The EUPHEMIA algorithm, market orders and constraints it supports, were carefully studied as well as some concepts associated to electricity markets to better understand its context and how the transition to the new algorithm was done.

The second step consisted of defining the simplified models that were to be created, the tools to use and to be familiarized with them. Therefore, two models were developed one having only simple hourly orders and the second one besides supporting simple orders should also handle complex orders and its constraints. The *Python* language was the chosen one to implement the mathematical models.

The third step involved selecting the data to collect regarding market orders and complex constraints and proceed with the simulation to obtain results for the day-ahead market. Consequently, two days in the past were chosen, one of which Market Splitting happened, so data for simple hourly orders was collected from [4]. Regarding complex orders there was no public available data, therefore it had to be specified in order to continue the work.

Finally, the models were tested using the collected data and the day-ahead market was simulated. When comparing the obtained results to the real prices and quantities it is possible to conclude that the main goal of this work was achieved.

1.3 Document Structure

The subsequent chapters are structured as follows.

Chapter 2 presents a brief description about the history of the electric system from its beginning to the point where it is nowadays, as well as its different models regarding different markets. After it, context is given within the day-ahead market coupling principle and the PCR project since it was mainly the reason why EUPHEMIA was created. This project was an initiative of seven PXs, therefore a succinct explanation regarding the rules of those markets is also presented, with emphasis on MIBEL since it is the main focus of this thesis.

Chapter 3 is divided in four main sections and it is entirely about EUPHEMIA, presenting a more detailed description of the algorithm. The first section is an overview of the algorithm giving a general idea of how it works. Sections two and three have a thorough explanation about how the transmission network is taken in consideration and all different market orders EUPHEMIA supports, respectively. The last section elucidates how the algorithm is structured, demonstrating its sub-problems and how to deal with its hindrances.

Chapter 4 gives information about the models developed for this dissertation. It has three main sections where both models are presented and the results are discussed. The first and second sections are divided into three subsections that give explanation about the mathematical formulation, algorithm, implementation and the obtained results for each model. Both models are applied to the Iberian Market universe and are a simplistic representation of the day-ahead problem given that not all constraints and real data could be considered. Nonetheless, these models allow the resolution of the day-ahead clearing procedure with accuracy. Model 1 solves the problem considering only simple hourly orders, whilst the second model takes complex orders into account. In the third section a comparison between both models is provided, mainly regarding the effect of the constraints that were applied, along with an assessment of their fragilities.

Lastly, Chapter 5 presents the conclusions reached with this thesis and future work that may be considered to improve what was done as well as other approaches to the algorithm that might allow different studies and analysis, such as long term exploration of the transmission network and interconnections.

Chapter 2

State of the Art

This chapter introduces concepts concerning electricity markets and the PXs involved in the PCR project and gives a brief explanation about the evolution over time until the present day of the electric system.

2.1 History of the Electric System

Since the last decade of the XX century, the electric industry was constituted mainly by companies that had a vertical integrated structure and were engaged in production, transmission, distribution and commercialization of energy. Even if several different companies were operating in the same country, there were concession areas assign to each of them, without any competition [5].

For several years, the organization of the sector was based on a monopolistic regime, which by its nature can be composed by a single supplier than by multiple ones, as a result of the economies of scale associated with high fixed costs, therefore generating reasonable returns of investment. So consumers could not choose freely the service provider and prices were obtained by unclear tariff regulation procedures [5].

Until the oil crisis of 1973, economy had very low rates of inflation and interest, and infrastructure costs were stable. There were high annual increases in demand with inflation and interest rates that remained unchanged from year to year. Thus, the prediction of demand was easy to determine, which facilitated the planning tasks since the risk was practically none [6, 7].

In 1973, Arab members of the Organization of Petroleum Exporting Countries (OPEC) had deliberately reduced their outflow of oil because of their dispute with Israel. These supply reductions affected nearly every European country that relied on imports from OPEC and created the fear that many countries would not be able to pay for the oil imports required to fuel their economies. Governments became aware that energy was a crucial concern and major changes would have to be done in their national systems in order to reduce the need for imported oil [6].

Security of supply in case of emergency, storage, and diversification of energy sources became areas of government interest. And a closer cooperation between countries began, to better coordinate their policies regarding the exploitation of energy sources, and distribution and consumption of energy, which led to the creation of an European energy policy [6, 7].

From then on, a number of initiatives were adopted that led to a restructuring of the energy sector. The decentralization and unbundling of production, transportation, distribution and commercialization activities was the main result of the liberalization of the sector, thus allowing the entry of new companies, that led to more competition between them. The creation of electricity markets has enabled citizens and companies to benefit from the liberalization of the electricity sector in the sense that better prices and services were achieved [6, 7].

Independent coordination and regulatory mechanisms have also been set up and entities were created, such as Market Operators, responsible for receiving and dispatching the market orders and Independent System Operators, responsible for verifying the assessment of the technical feasibility of the dispatched orders and for the operation of the system in real time [7].

2.2 Electricity Market Models

At a stage of deepening restructuring of the electricity sector, Pool markets became a form of relationship between the generation companies and eligible consumers.

These markets manage short-term balance generation and consumption, through supply and demand orders made from producers and consumers, respectively, with time intervals of normally 1 hour or 30 minutes. This is the concept of Day-Ahead Markets or Spot Electricity Markets, since these orders are conveyed the day before of their implementation. The purpose of a daily market, as an integral part of the electricity production market, is the execution of electricity transactions for the following day through the submittal of electricity sale and purchase bids by market agents [8]. Day-Ahead markets can be symmetric or asymmetric and voluntary or mandatory, further explained in subsections below [7].

2.2.1 Day-Ahead Symmetric Pool

In the symmetric pool, producers transmit their supply offers to the Market Operator specifying the availability of production for each time interval of the next day, and information about the injection node and the minimum price to receive. Eligible consumers and retailers also communicate demand orders to the Market Operator, specifying the desired power for each time interval, the absorption node and the maximum price they are willing to pay for each one of these intervals [7].

After the offers for each interval are submitted, they are organized by the Market Operator which later creates demand and supply aggregated curves for each time interval, making a purely economic dispatch based on prices. Demand orders are organized in a descendant manner of the price whilst supply orders are organized in an ascendant manner of the price. The intersection between the two curves gives the Market Clearing Price (MCP) and the respective electricity that will be traded, corresponding to the Market Clearing Quantity (MCQ). In Figure 2.1 there is an example of the intersection of the organized demand and supply curves. Supply offers with a price higher than the market price and demand offers with prices lower than the market price are not taken into consideration [9, 7].

If the dispatch is technically feasible, generator and load units whose orders were accepted, will receive and pay, respectively, electricity at the market price. With the exception of the last producer whose order was accepted, all producers will obtain a higher remuneration than the prices they have offered [7].

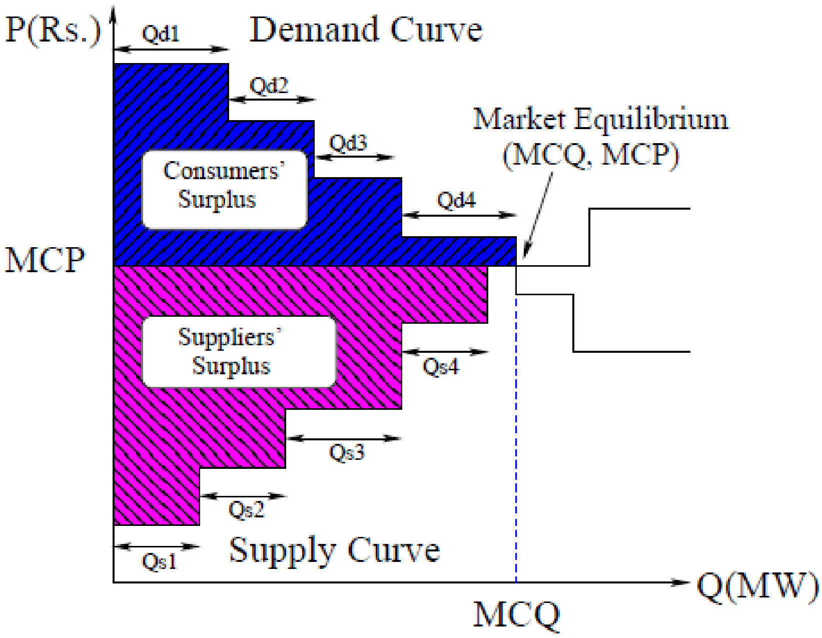

Figure 2.1: Market Equilibrium, from [9]

The main objective of a market clearing exchange is to maximize the Social Welfare Function (SWF), which is the sum of the consumer surplus and the producer surplus. The consumer surplus is achieved by multiplying the quantity by the difference between the offers price and the market clearing price. This is a surplus to the consumers in the sense that they get the quantity at lower price than their bidding price. The producer surplus is the product of the quantity times the difference between the market price and the offer price. In a fully competitive market, the offer price submitted by a supplier is in line with the marginal cost of production [9].

The mathematical formulation of the SWF is given as below.

$$Max\sum_{t}(\sum_{d}P_{d}^{t}.Q_{d}^{t}-\sum_{s}P_{s}^{t}.Q_{s}^{t}) \tag{2.1}$$

In the expression above, $P_{d}^{t}.Q_{d}^{t}$ are the price and quantity of the demand orders and $P_{s}^{t}.Q_{s}^{t}$ are the price and quantity of the supply orders. This is an optimization problem also subjected to constraints that are related to limits on the demand and generation bidding quantities, as well as an equality constraint ensuring that the cleared generation and demand quantities are equal. Further detail will be provided in chapters 3 and 4.

2.2.2 Day-Ahead Asymmetric Pool

Another possibility of market organization corresponds to the asymmetric model, in which the only orders presented to the Market Operator are the supply orders, with demand being usually modeled by load forecasts. It is assumed that the demand is completely inelastic and consumers are willing to pay any price necessary to supply all the demand.

Under these conditions, final prices are then strongly influenced by the level of demand and by the prices of which generators are producing [9].

Figure 2.2 shows a model for an asymmetric pool with demand forecast.

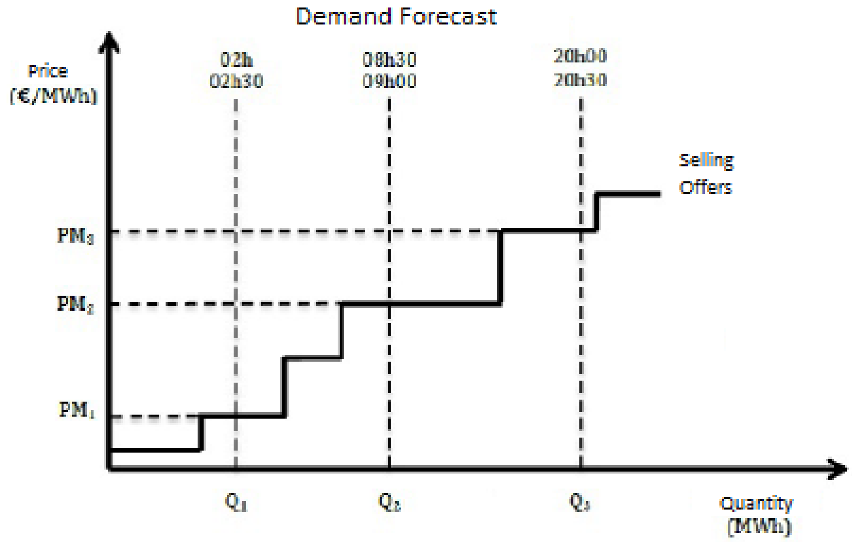

Figure 2.2: Asymmetric Pool

2.2.3 Market Splitting

The capacity that is available for the transit of energy between neighboring markets does not always allow the totality of the flow transition negotiated by the agents, which leads to congestion in the interconnections. In order to manage this congestion situation, there is a mechanism of separation of markets, also known as Market Splitting [10].

In Market Splitting, one system price is calculated in the first place, and if there is not enough transmission capacity between the zones, the area is split into a number of zones each of which has a price of its own [2]. The price is higher in markets that are importing energy.

Figure 2.3 shows an example of Market Splitting, where after determining that there is congestion in interconnections, a price for each zone is calculated.

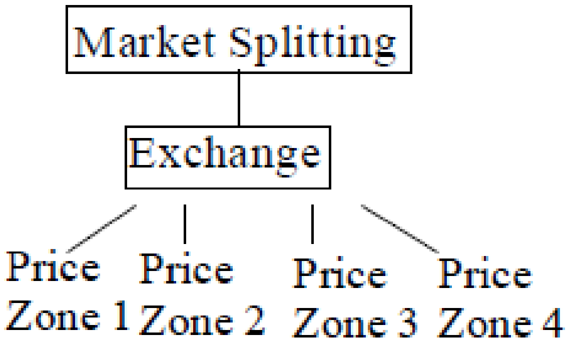

Figure 2.3: Market Splitting, from [2]

2.2.4 Bilateral contracts

Bilateral contracts market is a centralized market for bilateral trade where electricity is traded based on physical deliverable energy involving a generation company and a retailer or large consumer.

Market agents are identified and allow free commercialization of energy between producers and consumers for various time horizons, provided that these transactions are technically feasible. These contracts, have a minimum duration of six months, and allow producers, distributors, consumers and traders to negotiate all the conditions of supply, such as the duration, the quantity, the price and even quality issues. Although there is the advantage of guaranteeing predictability of prices, since it is defined in the contract, they also end up promoting a non optimized dispatch [7].

2.2.5 Mixed model

The mixed models result from the combination of the voluntary Pool model with the bilateral contracts. The technical validation of all physical contracts and Pool dispatches is performed by the System Operator who afterwards procures and contracts the necessary ancillary services. In situations where there is congestion, the System Operator returns the information once it received from the entities and activates adjustments, increasing or decreasing power, which may even resort in Market Splitting as mentioned before [7].

2.2.6 Intraday Market

The intraday market is a complementary platform to the day-ahead market, where adjustments of the power traded in the daily market are done. Its purpose is to attend energy offer and demand which may arise, in the hours following the day-ahead market [8]. It allows the management of congestions that may occur after the day-ahead market, ensuring the balance between energy being produced and demand and also allowing market agents to adjust their buying or selling positions, as defined in the day-ahead market. These markets are conducted in several daily predefined trading sessions, and the participation is usually subjected to the same conditions as in the day-ahead market [7].

2.2.7 Ancillary Services

Ancillary services are typically provided by market producers or by specific network equipments, and are divided into three sections, primary, secondary and tertiary reserves, as well as the control of voltage and reactive power. In Portugal and Spain, these services can be contracted in specific markets, which is the case of secondary and tertiary reserves, whilst the primary reserve is mandatory. These mechanisms were introduced in the market to ensure the security of system supply and are used by the System Operator [11, 12].

As mentioned before, in Portugal and Spain, primary regulation is a mandatory and an unpaid system service. The generators that are already producing, automatically and autonomously correct the instantaneous imbalances between production and consumption through frequency variation of the turbine speed regulators [11, 12].

The secondary reserve has the central role of maintaining the deviation of the interconnections within certain limits and also collaborates in the maintenance of joint frequency between regional markets. It will also act when there are sudden imbalances between production and consumption, which may be caused by the loss of generating sets or by sporadic deviations from consumption. In the Iberian Market, the generator units providing this service are controlled by Automatic Generation Control System (AGC) and the service is contracted in specific markets [11, 12].

Finally, tertiary regulation operates against strong system oscillations and is activated to substitute more expensive secondary regulation. As for secondary reserves, in Portugal and Spain, this service is contracted by the System Operators [11, 12].

2.3 Day-Ahead Market Coupling Principle

Day-ahead market coupling is a method to integrate different energy markets into one coupled market, which means energy transactions are no longer restricted to local territorial scope. Instead, these transactions may involve buyers and sellers from different areas [3].

The main advantage of such approach is the improvement of market liquidity and transparency, as well as the existence of less volatile electricity prices across Europe. It also brings benefits to market players, since there is no need for acquiring transmission capacity rights to carry out cross-border exchanges, after all, these are given as a result of the market coupling mechanism.

Market players have to submit their orders, in their respective PX, which will be matched with other competitive orders in any area involved, having in mind that network constraints are to be respected [3, 13].

PXs offer a trading platform to exchange members submitting bids for buying and selling power. They organize markets that are optional, anonymous and accessible to all participants satisfying admission requirements. The main objective of a PX is to ensure a transparent and reliable wholesale price formation mechanism on the power market by matching supply and demand at a fair price and ensure that the trades done at the exchange are finally delivered and paid [14, 15].

2.4 PCR Project

Price Coupling of Regions is the project resulting from the synergy of seven European PXs to develop a single price coupling solution to calculate day-ahead electricity prices across Europe respecting the capacity of the relevant network elements on a day-ahead basis. It began in 2009, as an initiative of three PXs (OMIE, Nord Pool and EPEX SPOT), later on four more (GME, OPCOM, OTE and TGE) joined the project and it is currently opened to other European PXs wishing to join [16, 17].

Figure 2.4 shows all countries involved in the project and, as one can see, the majority of countries in Europe already joined PCR.

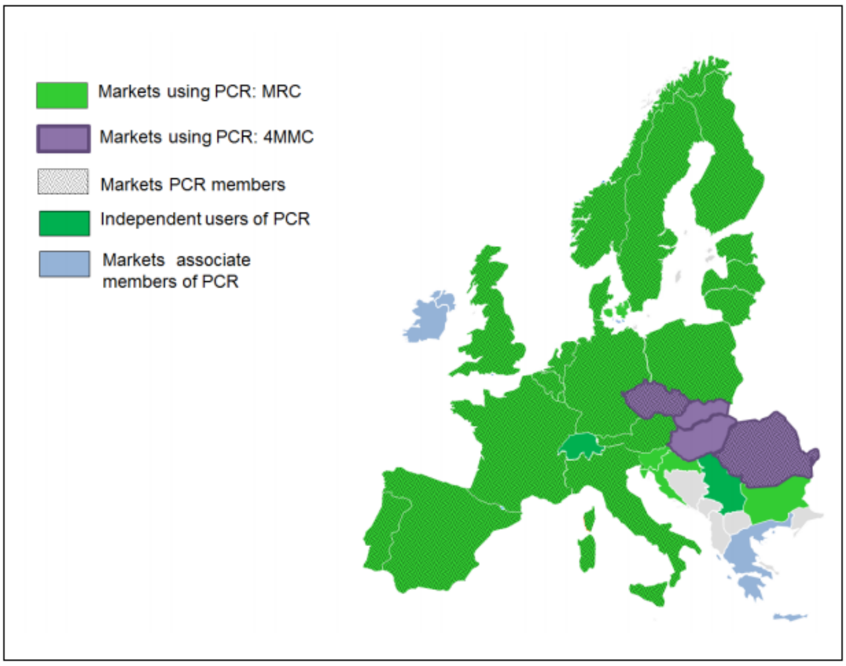

Figure 2.4: Countries in PCR project, from [3]

Giving that seven PXs are involved in the PCR project, this means that the electricity markets in several countries across Europe are covered. One of the main features of the PCR project is the development of an algorithm, the EUPHEMIA, to be used by all PXs involved, in order to deliver an efficient price coupling.

Nowadays, EUPHEMIA is used daily to compute in a coupled way day-ahead electricity prices for 23 European countries (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and United Kingdom) with an average daily value of matched trades over EUR 200 million [3, 17, 18].

This algorithm was first developed in July 2011 and it operated for the first time on the 4th of February 2014 incorporating markets in North Western Europe and South Western Europe. Since then it has evolved and improved, being able to integrate GME since February 2015. It was built using the existing local algorithm, COSMOS, that was in use since November 2010, in the Central Western Europe region [3, 19].

EUPHEMIA is owned by the corresponding PXs while supported and upgraded on a regular basis by N-SIDE, a company based in Belgium, that provides maintenance, upgrade and support services [18].

The next subsections provide insights on some of the involved regional markets.

2.4.1 EPEX SPOT

The EPEX SPOT corresponds to the PX involving Germany, France, United Kingdom, Netherlands, Belgium, Austria, Switzerland and Luxembourg, as illustrated in Figure 2.5. In 2015, the EPEX SPOT integrated with former APX Group, which was a PX operating the spot markets in the Netherlands, the United Kingdom, and Belgium [14].

This PX runs the day-ahead market, intraday market, bilateral contracts and ancillary services for all countries mentioned above, which together account for more than one third of the European power consumption [14].

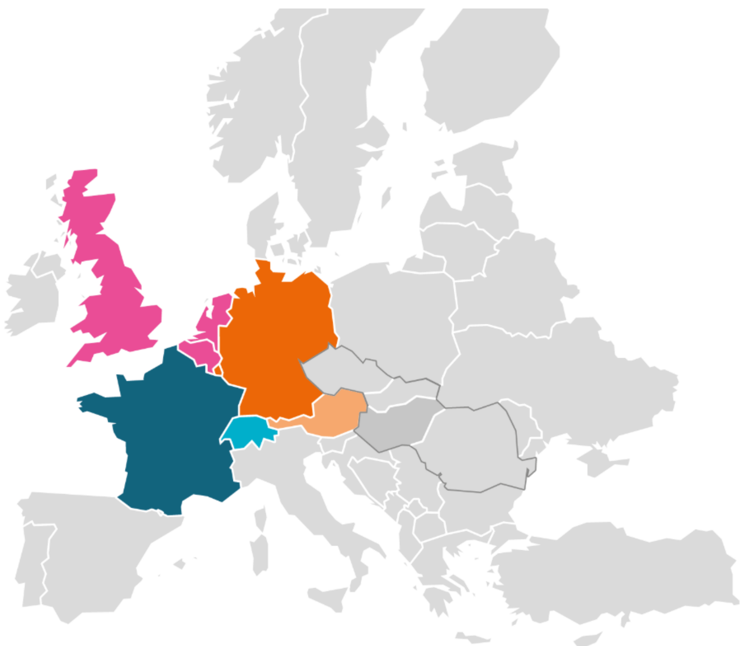

Figure 2.5: Countries in EPEX SPOT, taken from [14]

2.4.2 GME

The GME is the PX which operates trading energy markets in Italy, comprising day-ahead market, intraday market, bilateral contracts and ancillary services [20].

The Italian network is partitioned in grid sections that are called zones, and as seen in Figure 2.6 there are six different areas. A zone is a portion of the national transmission grid, *Rete di Trasmissione Nazionale* (RTN) with specific transit limits of energy [20].

GME uses the zonal simplified representation of the network to test and remove congestions created either by the market or by bilateral contracts.

Figure 2.6: Zones in GME, taken from [20]

Usually the price used in the supply offers of the electricity market is the clearing price of the zone to which they belong, but on the other hand, the accepted demand bids are evaluated at the single national price, *Prezzo Unico Nazionale* (PUN), which is defined as the average of the zonal prices weighted by zonal consumption and represents the purchase price or end customers [3, 21].

2.4.3 Nord pool

Nord Pool runs the day-ahead and intraday markets of in Norway, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Germany and the United Kingdom, as illustrated in Figure 2.7 [22].

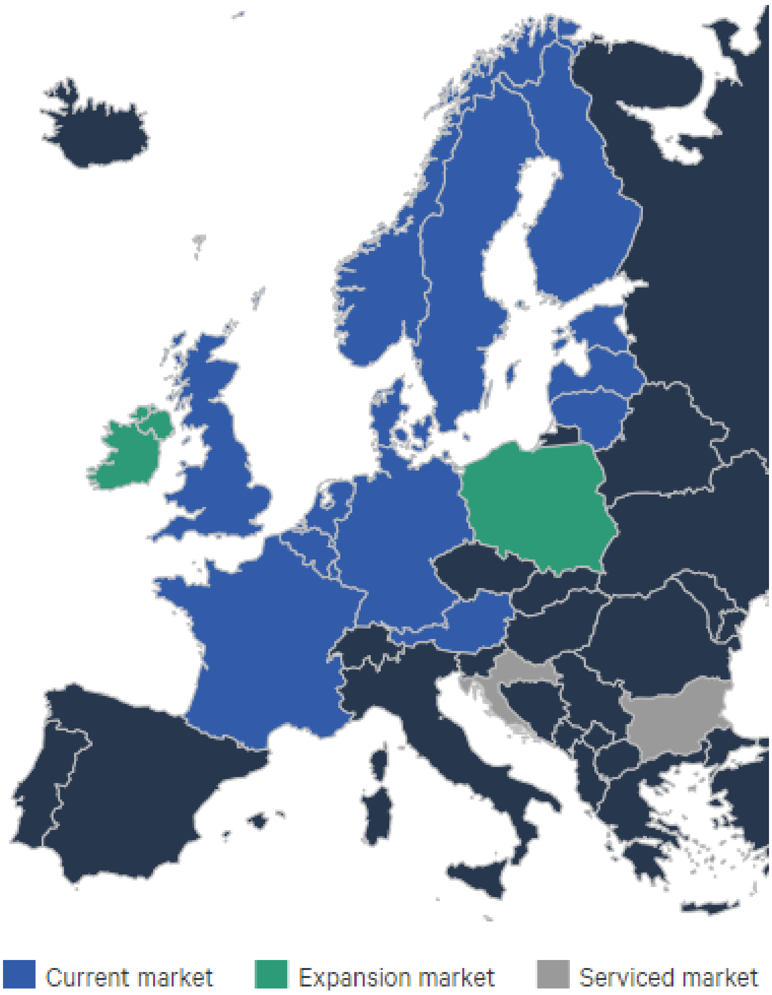

Figure 2.7: Countries in Nord Pool, taken from [22]

This PX has markets divided into several areas and its division is decided for each Nordic country by the Transmission System Operator (TSO). The number of Norwegian areas can vary, but for now there are five. Eastern Denmark and Western Denmark are always treated as two different areas. Finland, Estonia, Lithuania and Latvia constitute one bidding area each. Sweden was divided into four different areas on 1 November 2011 [22]. Figure 2.8 shows the mentioned areas in Nord Pool.

The different areas help indicating constraints in the transmission systems, and ensure that regional market conditions are reflected in the price. Nord Pool calculates a price for each bidding area for each hour of the following day based on the market splitting mechanism in case there is congestion between any pair of areas [22].

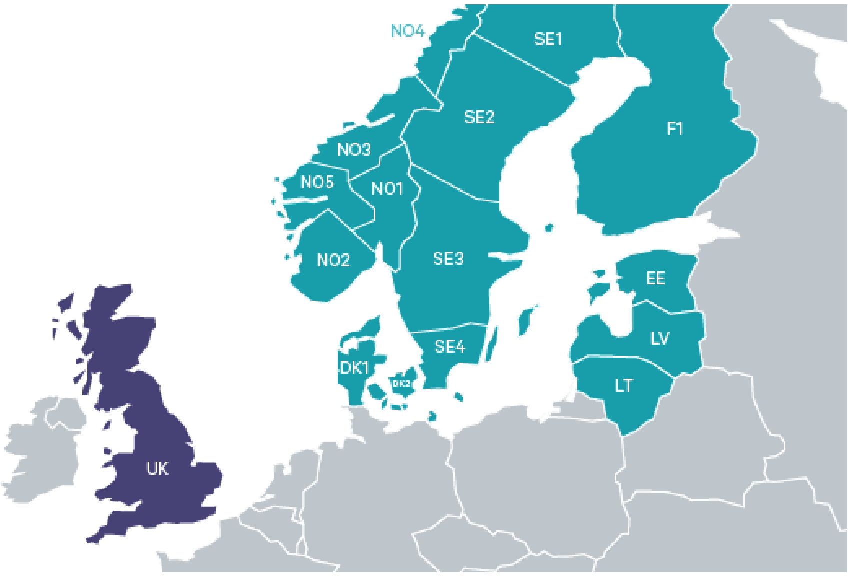

Figure 2.8: Areas in Nord Pool, taken from [22]

2.4.4 OPCOM

OPCOM is the PX in charge of running the Romanian day-ahead, intraday and bilateral contract markets [23].

There is also a Green Certificate market which works in parallel to the day-ahead market, where suppliers are obliged to buy a fix quota of electricity, established by the regulator entity, that comes from renewable sources. The producer receives a Green Certificate for each MWh of electricity delivered into the network, which is then sold on the Green Certificates Market [23].

This mechanism promotes the production of electricity from renewable sources since it represents an additional income for the renewable producers [23].

The Romanian market has two trading zones, one is the National Trading Zone which corresponds to the part of the national power system, and the Border Trading Zone which is constituted by the neighboring countries.

The reason behind the creation of these two areas is related with management of congestion, as it is in other PXs, and can only occur in lines connecting Romania to its borders [23].

2.4.5 OTE

OTE is the PX that handles day-ahead, intraday electricity and gas markets for Czech Republic. There is also a block market for electricity, where the trading is based on the forward principle, which means the product is financially settled following the delivery for the price of the completed trade in matching within the framework of a continuous trade (the trade price) [24, 25].

2.4.6 TGE

TGE is the PX running the electricity and natural gas markets in Poland. The key areas of operation are the day-ahead market, intraday market and forward contracts for both electricity and gas [26].

2.5 MIBEL

The Iberian Electricity Market operates trading energy markets in Portugal and Spain and resulted from the willingness of the Portuguese and Spanish Governments in integrating the electric systems of both countries. The consequences of this cooperation made a significant contribution not only towards establishing an electricity market at the Iberian level but also at the European level, as it is an important step towards the integrated energy market [10, 27].

This on-going development started in 1998, but it was only in 2001 that the Protocol for the Cooperation between the Spanish and Portuguese Government was signed to establish the Iberian Electricity Market. However, MIBEL was fully launched and started operating years later on July 1 of 2007 [27].

The work to coordinate conditions between the two electric systems had finally been achieved with the expectation of bringing benefits for consumers in both countries, guaranteeing access to all stakeholders in conditions of equality, transparency and objectivity.

MIBEL allows any consumer of the Iberian area to acquire energy in a regime of free competition to any producer operating in Portugal and Spain.

The main goals of the Iberian market are related to the promotion of the development of the market in both countries, as well as operate under transparency principles, free competition, objectivity, liquidity, self-financing and self-organization [27].

With the completion of MIBEL, a set of procedures, rules and economical and technical conditions were agreed between Portugal and Spain. In this context, it was defined the creation of an Iberian Market Operator responsible for the management of the organized markets, which would be based on a bipolar interconnected structure. OMIE (*Operador del Mercado Ibérico de Energía* - Spanish Polo) manages the day-ahead and intraday markets and OMIP (*Operador do Mercado Ibérico de Energia* - Portuguese polo) is in charge of managing forward markets [27].

MIBEL runs a mixed market model that gives a price for each of the 24 hours of each day of each year. In the daily market the energy transactions are made to be delivered the day after the negotiation. The demand bids and production offers are managed in an online computer system. This platform, in which Portugal and Spain are integrated, is managed by OMIE, and the trading time is dictated by the Spanish time zone [10].

OMIE therefore manages the Iberian day-ahead and intraday electricity markets where purchase and sale transactions are carried out due to the participation of market agents in the sessions that combine the Spanish and Portuguese areas of MIBEL. However, each operator of the Portuguese and Spanish transmission networks are responsible for the operation of their respective power system [27].

The market clearing price is obtained through a process in which the supply offers (supply curve) are ordered in an increasing way of their price, and the demand bids (demand curve) are decreasing in price. The market price is the lowest price which ensures the supply meets the demand [28]. Market orders can be simple hourly and complex. The latter is of four different types, further explained in the next chapter.

The functioning of the day-ahead market in which Portuguese agents participate means that all buyers pay the same price and all sellers receive the same price, the MCP [12].

However, as the daily market comprises both Portugal and Spain, it is necessary to check the situation where commercially available interconnection capacities between the two countries do not support the cross-border flows of energy that cross-market offers would dictate. If this happens, the Market Splitting mechanism is activated and the pricing algorithm is executed separately for each area. Thus, prices will be different for each area in those periods [10, 27].

Following the day-ahead market, there are six sessions of the intraday market. In these markets stakeholders can resubmit supply and demand orders in hiring sessions held up to 4 hours before the actual time [27].

Table 2.1, shows the time schedule for the intraday sessions in MIBEL.

Table 2.1: Intraday Sessions, taken from [4]

	Session 1	**Session 2**	**Session 3**	**Session 4**	**Session 5**	**Session 6**
Session Opening	17:00	21:00	01:00	04:00	08:00	12:00
Session Closing	18:45	21:45	01:45	04:45	08:45	12:45
Matching Results	19:30	22:30	02:30	05:30	09:30	13:30
Reception of Breakdowns	19:50	22:50	02:50	05:50	09:50	13:50
Publication PHF	20:45	23:45	03:45	06:45	10:45	14:45
Schedule Horizon (Hourly Periods)	27h (22-24)	24h (1-24)	20h (5-24)	17h (8-24)	13h (12-24)	9h (16-24)

As mentioned before in subsection 2.2.7, in both Portugal and Spain, primary regulation is mandatory and secondary and tertiary regulations are contracted by System Operators in specific markets. Closer to the operation day, System Operators activate and manage those specific markets to procure and contract secondary and tertiary reserves [12].

These markets are managed separately by each operator, although some degree of supply of tertiary reserve from agents located in the other country is currently admitted.

To avoid situations of congestion and consequent activation of Market Splitting procedure, some initiatives have been developed to strengthen the interconnections between Portugal and Spain.

Table 2.2 presents the maximum technical capacity of transmission for each of the interconnection lines under normal operating conditions, in winter and summer.

Currently there are ten lines that interconnect the electrical systems of Portugal and Spain, six of which of 400 kV, three of 220 kV and one interconnection of 130 kV [29, 30].

From Portugal to Spain, the interval of available capacity for trading purposes values is from 2700 MW to 4000 MW, and in the opposite direction, from Spain to Portugal, lower values of capacity are reached from 1800 MW to 3100 MW [29].

Table 2.2: Technical Capacity of the Interconnections, taken from [29]

kV	Interconnection	Capacity in Winter [MVA]	Capacity in Summer [MVA]
400	Alto Lindoso - Cartelle 1	1660	1390
	Alto Lindoso - Cartelle 2	1660	1390
	Lagoaça - Aldeadávilla	1706	1469
	Falagueira - Cedillo	1663	1400
	Alqueva - Brovales	1386	1280
	Tavira - Puebla de Guzmán	1386	1386
220	Pocinho - Aldeadávilla 1	435	374
	Pocinho - Aldeadávilla 2	435	374
	Pocinho - Saucelle	430	360
130	Lindoso - Conchas	131	90

The map shown in Figure 2.9 gives an overview of the interconnections between Portugal and Spain.

Figure 2.9: Interconnections between Portugal and Spain, from [30]

2.6 Summary

This chapter presents a description about the State of the Art in regard of electricity markets in Europe in order to provide context and all the information necessary about the integration of the regional European markets into one Single European Market. This is crucial to understand the role of the EUPHEMIA algorithm as well as its procedures, that will be described in great detail in the following chapter.

Chapter 3

EUPHEMIA Description

This chapter presents a detailed description of the EUPHEMIA algorithm and all concepts required to formulate the problem and it serves as a theoretical basis for the next chapter where a simplified model is described.

3.1 Overview

EUPHEMIA is the algorithm developed to solve the problem resulting from the coupling of the day-ahead power markets in the PCR region. It calculates energy allocation and electricity prices across Europe, by maximizing the overall welfare and increasing the transparency of the computation of prices and flows [3].

Initially, all market participants submit their orders to their respective PX, which are collected and provided to EUPHEMIA as input data. Afterwards, and taking in consideration all constraints related to these orders and to the grid, the algorithm generates as outputs the hourly market clearing prices for the next day, the matched volumes and the net position of each bidding area, as represented in Figure 3.1 [3].

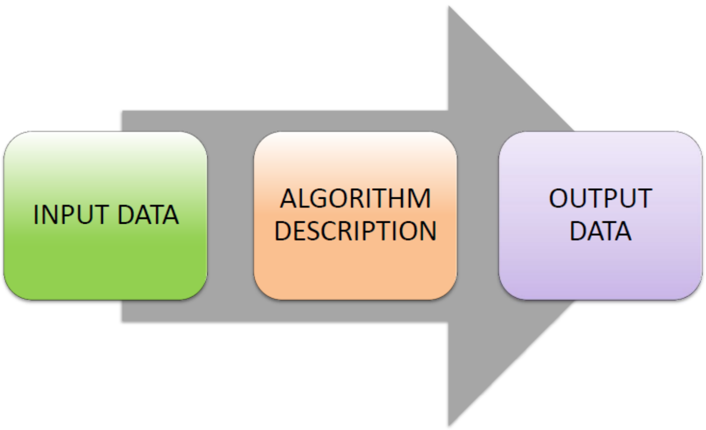

Figure 3.1: General Description taken from [3]

In the next subsection, detail regarding the Power Transmission Network model, market orders and the solution algorithm will be provided.

3.2 Power Transmission Network

EUPHEMIA takes into consideration the power transmission network to ensure that the output of the algorithm is feasible and respects all technical and physical limitations of the grid.

Therefore, it receives information about the power transmission network provided by the TSOs in the form of constraints that must be respected by the final solution.

Knowing that a bidding area is the smallest entity used to represent a market where orders can be submitted and energy can be exchanged, EUPHEMIA determines a market clearing price for each bidding area of each period [3].

Along with the prices, it also computes the corresponding net position, calculated as the difference between matched supply and matched demand quantities belonging to the same bidding area. Net positions may also be subjected to limitations regarding variations between periods [3].

In this model, the transmission capacity on an interconnector integrates the spot markets in each different bidding area in order to maximize the social welfare. Thus, the auctioning of transmission capacity is included implicitly in the auctions of electrical energy in the market, instead of being auctioned separately and independently from the spot market [31, 32].

Cross-border electricity trading fundamentally requires a coordinated capacity calculation and allocation mechanism. Coordination across bidding zones is essential since power flows cannot be restricted by commercial agreements but follow the laws of physics [33, 34].

For example, when Germany exports electricity to France, part of the electric power will flow through the Netherlands and Belgium, instead of following the direct path between the two countries. As such, this transaction also has an impact on the remaining interconnection capacity at the Dutch and Belgian borders [35].

Additionally, EUPHEMIA supports ramping requirements that can be imposed on the net position on an hourly or daily basis. The first being a limit on the variation of the net position of a bidding area from one hour to the next and the second being a limit on the amount of reserve capacity that can be used daily.

Within the European PCR, there are three different patterns of transit capacity allocation, further explained in the following subsections.

3.2.1 Available Transfer Capacity Model - ATC

The ATC is a measure of the transfer capacity remaining in the physical transmission network for further commercial activity over and above already committed uses. This makes ATC computing important to power market participants, to system operators, and to transmission planners [36].

Each TSO determines a Net Transfer Capacity (NTC) value for each direction on each border of its control area. The NTC value can be interpreted as the maximum allowable commercial exchange between two zones that pushes at least one critical network element to its physical limit. [35].

The Net Transfer Capacity (NTC), is derived from the Total Transfer Capacity (TTC), after deducting a Transfer Reliability Margin (TRM). While the TTC is the maximum commercial exchange possible between two zones in one direction, the TRM is reserved to be able to cope with emergency situations or unexpected deviations in neighbouring zones. Finally, to arrive at the ATC value, the long-term cross-border nominations are subtracted from the NTC value. The deduced ATC is subsequently available for cross-border trade on the day-ahead market [35].

$$E_{a,b} \leq ATC_{a,b} \tag{3.1}$$

In (3.1), $E_{a,b}$ is the commercial exchange from zone a to b in MW, and $ATC_{a,b}$ is the available transfer capacity exchange from zone a to b, also represented in MW.

In EUPHEMIA, bidding areas are linked by interconnectors and energy flows only through these lines and is limited by their ATC.

As seen in Figure 3.2, lines are oriented from a source bidding area (A) to a sink bidding area (C) and a positive value of flow indicates it goes from A to C, whilst a negative value indicates it flows on the opposite direction. ATC limitations can also be negative and different per period and direction of the line. A negative ATC value in the same direction of the definition of the line from A to C is implicitly indicating that the flow is forced to only go in the direction from C to A [3].

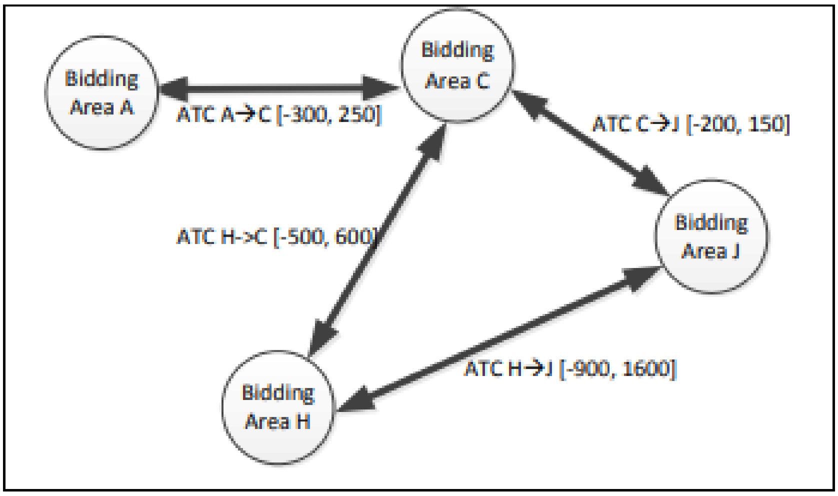

Figure 3.2: Bidding areas connected in an ATC Model, from [3]

In this model, lines could be operated by merchant companies who charge by the MWh that passes through the cables. And, since there might be losses in flow through an interconnection, which means part of the energy received at the end of the line is less than the energy initially sent, a flow tariff is included in the algorithm.

Figure 3.3, shows that when bidding area B is injecting 1000 MWh in bidding area A through an interconnector, only 950 MWh reach their destination. This happens because there are losses of 5% in the interconnection, meaning that 50 MWh are consumed in the line.

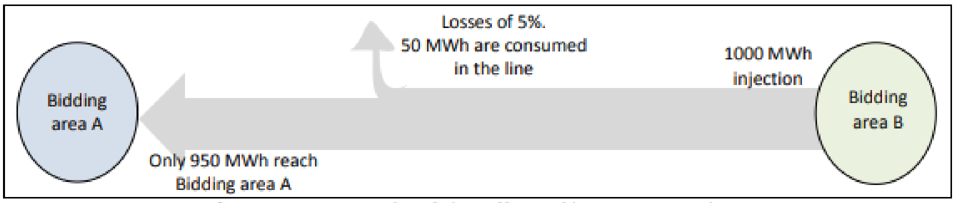

Figure 3.3: Losses in a line, taken from [3]

A congestion rent measures for each interconnector traversed by a flow the difference between the total amount of money to be paid to the supplier of this flow at one end of the interconnector and the total amount of money to be received from the consumer of this flow at the other end of the interconnector. The aforementioned flow tariff is included as a loss with regard to the congestion rent, which shows up as a threshold for the price between the connected bidding areas.

If the difference between the two corresponding market clearing prices is less than the tariff, then the flow will be zero. On the other hand, if there is a flow, the price difference will be exactly the flow tariff, unless there is congestion. Once the price difference exceeds the tariff the congestion rent becomes positive [3].

The presence of losses on the interconnector will not impact the congestion rent, however, if the interconnector implements tariffs, the congestion rent will be reduced by the product of the tariff rates and the implicit flow obtained by EUPHEMIA.

Ramping constraints regarding hourly flow variations can be applied to individual lines and line sets to limit flow movement from one hour to the next. The maximum increment of flow is called ramping up while the maximum decrement is termed as ramping down. These ramping limits may be different for each period and direction. For period 1 of a given day, the limitation of flow takes into account the value of the flow of the last hour of the previous day. When ramping constraints are applied to groups of interconnectors, the sum of the flows through a set of lines is restricted by ramping limits [3].

3.2.2 Flow Based Model - FB

The FB model, is an alternative to the ATC, in which a more precise modeling of the physical flows is obtained when handling network constraints, therefore leading to a more efficient use of generation and transmission resources [3].

Under the ATC model, TSOs determine the commercial capacities available per direction on each border whilst the flow based methodology formulates the constraints which reflect the physical limits of the grid [33, 35].

Subsequently, taking into account the physical flows induced by each trade, the flow-based algorithm itself decides how transmission capacity is allocated over market parties. More capacity is offered to the market, resulting in a solution equal or better in terms of social welfare.

In this model, constraints are given by means of the Remaining Available Margin (RAM), which translates into the number of MW available for exchanges, and by the Power Transfer Distribution Factor (PTDF). These coefficients indicate how many MWh are used by the net positions resulting from the exchanges, and it models the physical path of electricity in a simplified way [3, 33].

This means that the PTDF coefficients translate the line flows into linear constraints using the net positions of each bidding area. The relation between the flow, the net position (NP) and the RAM is expressed in (3.2) [37].

$$\sum_{node} PTDF. \sum_{node} NP \geq RAM \tag{3.2}$$

Net position in this context should be understood as the net position of a market as a result of the exchanges via the meshed network, excluding the exchange via ATC lines. NP is the vector of net positions which are subject to the flow based constraints.

The flow based modeling might result in non intuitive situations that happen when energy goes from high priced areas to low priced areas. These situations might occur when markets with lower market clearing prices have higher demand requirements, therefore importing energy from more expensive ones. Non intuitive situations happen because some of these exchanges free up capacity, allowing even larger exchanges between other markets [3].

The mechanism used by EUPHEMIA to suppress these non intuitive exchanges resides in the fact that PTDF constraints are applied to the flows rather than directly on the net positions, so it seeks flows between areas that match the net positions [3].

Another side effect of the model is the flow factor competition in case of market curtailment at maximum price. If several markets end up at maximum price in a flow based domain, the PTDF coefficients can lead to unfair distribution of the available energy and in some extreme cases, the solution that maximizes the welfare is the one where one market is totally curtailed while all the available energy is given to another market which is not necessarily at maximum price [3].

EUPHEMIA implements a mechanism that allows a fairer distribution of the curtailment between all the markets in a flow based domain.

3.2.3 Hybrid Model

The hybrid model results from the combination of the two previous models, since some bidding areas use the FB model and other the ATC model [38].

3.3 Market Orders

After market participants have submitted all orders to their respective TSO, these are provided to the algorithm as inputs. Market orders have different characteristics depending on their local market rules.

The following nomenclature is used regarding the acceptance of market orders and market clearing prices [3]:

- A demand (supply) order is said to be *in-the-money* when the market clearing price is lower (higher) than the price of the hourly order and these orders must be fully accepted.
- A demand (supply) order is said to be *at-the-money* when the price of the hourly order is equal to the market clearing price and these orders can be either fully or partially accepted or rejected.
- A demand (supply) hourly order is said to be *out-of-the-money* when the market clearing price is higher (lower) than the price of the hourly order and these orders must be fully rejected.
- *fill-or-kill* an order which is either totally rejected or totally accepted.

The following subsections contain a brief explanation about all different orders.

3.3.1 Simple Hourly Orders

Simple hourly orders are defined as electricity bids which are submitted for each hourly scheduling period and unit, with the expression of a price and an amount of power [8].

There are three different types of simple hourly orders, further explained below.

- **Linear Piecewise Aggregated Curves** - That contain only interpolated orders. In these curves, two consecutive points of the monotonous curve cannot have the same price, except for the first two points defined at the maximum and minimum prices of the bidding area. Demand bids are arranged by descendant order and generation bids by ascendant order of their prices, as illustrated in Figure 3.4 [3].

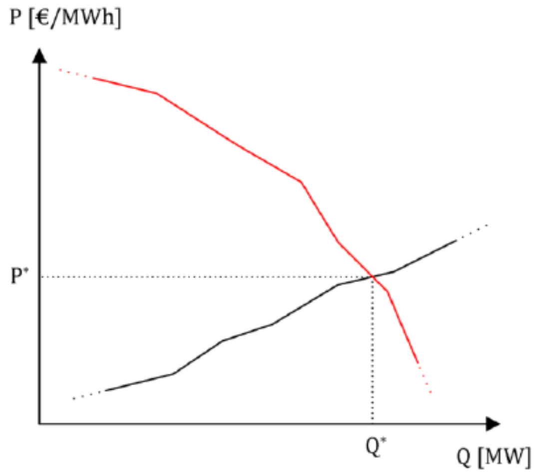

Figure 3.4: Linear Piecewise Aggregated Curves, taken from [38]

- **Stepwise Aggregated Curves** - That contain only step orders. These curves, have two consecutive points that have always either the same price or the same quantity. For each hourly scheduling period within the same daily scheduling horizon, there can be as many as 25 power blocks for the same unit, with a different price for each of the blocks and with prices increasing for selling bids and decreasing for purchasing bids. This is illustrated in Figure 3.5 [3, 8].

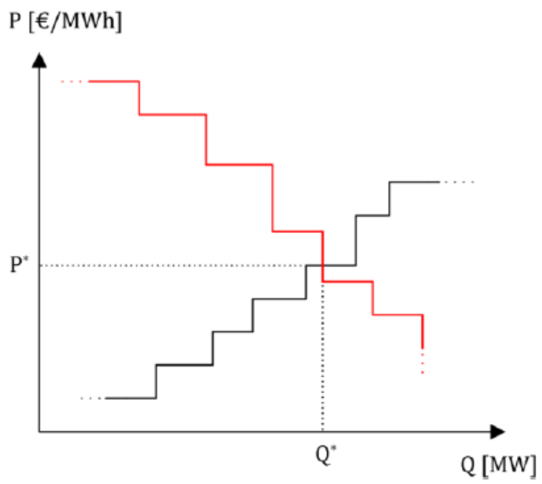

Figure 3.5: Stepwise Aggregated Curves, taken from [38]

- **Hybrid Curves** - That contain both interpolated and step orders, being composed by both linear and stepwise segments, as illustrated in Figure 3.6 [38].

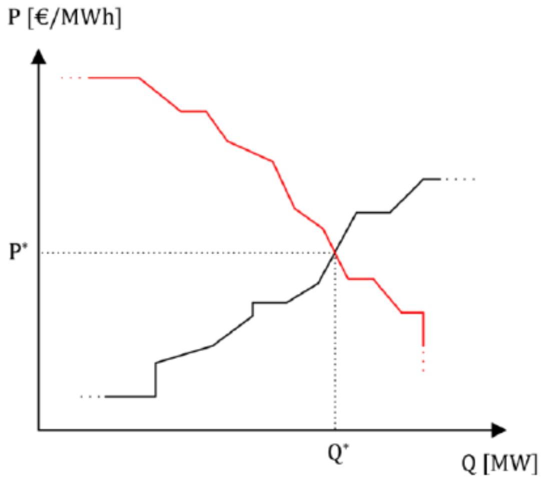

Figure 3.6: Linear Piecewise Aggregated Curves, taken from [38]

3.3.2 Complex Orders

Complex orders are defined as electricity bids that, while complying with the requirements of simple stepwise hourly orders, also include all, some or any one of the complex conditions, further described below [3, 8].

- **Indivisibility Condition** - It certifies that the indivisible block of a bid should be matched in its entirety and not for a fraction of the power. Supply orders are allowed to include this constraint in a selling bid for the first block of the 25 possible blocks in each hourly scheduling period and in the ones which do not specify any other complex condition [8].

- **Minimum Income Condition (MIC)** - Energy sellers may want to guarantee that the bid should only be considered submitted for matching purposes if the amount of money collected by the order in all periods covers its production costs, guaranteeing a minimum income. The minimum income required is defined by a fixed term, that represents the startup cost of the unit, and a variable term multiplied by the assigned energy, that represents the operation cost of a power plant. This condition should not be allowed if the income requested exceeds the income resulting from the complete acceptance of the bid at the price bid by more than 100%. In the final solution MIC orders are activated or deactivated as a whole, and will not contain active MIC orders that do not fulfill their MIC constraint [3, 8, 39].

- **Scheduled Stop Condition (SSC)** - Market participants that have submitted a MIC order are allowed to use Scheduled Stop, which will alter the deactivation of the MIC and it does not imply the automatic rejection of all the hourly sub-orders. For instance, SSC may be used in case a power plant was operating the previous day and its owner does not want to abruptly stop its production in case the MIC order is deactivated. The first block of the first three hourly scheduling periods of the daily scheduling horizon can be treated as simple bids. The electricity bid that includes the SSC should be decreasing during the three hourly scheduling periods [3, 8, 40].

- **Load Gradient Condition (LGC)** - It defines, for each production unit, a maximum upward and downward difference in energy variation for two consecutive hourly scheduling periods. The amount of energy that is matched in one period is limited by the amount of energy that was matched in the period before and is also related with the energy to be scheduled for the next period [3, 8].

3.3.3 Block Orders

Suppliers with generators that have high start up or shut down costs may find hourly orders economically inefficient, so block orders were created to allow traders to sell electricity for several time slots with a single bid. This concept is useful for producers, since it allows to recover costs and model technical constraints, but also for consumers because it provides security concerning their base load. A block order is defined by having one price, a set of periods, quantities associated to periods and a minimum acceptance ratio. Although these characteristics define a block order, some might change slightly considering all different types of block orders [9, 41].

- **Regular Block Orders** - These orders correspond to the simplest case, where an order is defined by a single price and one single quantity for a consecutive set of periods. These are called *fill-or-kill* because they are either totally rejected or totally accepted. If a regular block order is *out-of-the-money* it should be totally rejected [16].

- **Profile Block Orders** - This type of block order is defined by a single price and different quantities for each hour. It can only be accepted if the acceptance ratio is higher or equal to the minimum accepted ratio. If a profile block order is *out-of-the-money*, it should be totally rejected [16].

- **Linked Block Orders** - Block orders can be linked together in a parent-child relationship, when the acceptance of individual block orders is dependent on the acceptance of other block orders. The dependent ones are designated child blocks and the independent ones are parent blocks. The acceptance ratio of a child block should be at most the lowest acceptance ratio among its parent blocks and the acceptance ratio of a parent block should be greater than or equal to the highest acceptance ratio of its child blocks. Parents can be accepted alone but not the child since it always needs the acceptance of the parent first. However, partially acceptance of child blocks can save the parent block when the surplus of the family is not negative and when leaf blocks (block order without child blocks) do not generate welfare loss. A parent block which is *out-of-the-money* can be accepted in case its accepted child blocks provide sufficient surplus to at least compensate the loss of the parent. A child block which is *out-of-the-money* cannot be accepted even if its accepted parent provides sufficient surplus to compensate the loss of the child, unless the child block is in turn parent of other blocks. In an easy common configuration of two linked blocks, the rules are easy to understand. The parent can be accepted alone, but not the child that always needs the acceptance of the parent first. The child can save the parent with its surplus, but not the opposite [3, 16, 42].

- **Exclusive Block Orders** - An exclusive group is a set of block orders in which the sum of the accepted ratios cannot exceed 1 [3].
- **Flexible Hourly Block Orders** - With flexible orders, participants can buy or sell electricity in a specific area in exactly one hour without specifying the hour, which is later on determined by the algorithm. It is basically, a regular block order which lasts for only one hour. It has a fixed price limit, a fixed quantity, minimum acceptance ratio of 1, with duration of 1 hour [3, 9, 16, 42].

3.3.4 Merit and PUN Orders

Merit orders are individual step orders that have an assigned merit number that is used to rank them. Lower numbers of merit have higher priority and should be accepted first unless constrained by other network conditions [3].

These orders belong only to the GME market and are categorized in three types [16, 20].

- **Supply Merit Orders** - They are selling offers and are cleared at the bidding area price of which they belong [20].
- **Demand Merit Orders** - All buying bids from pumping units and buying bids in non-Italian national zones. These are also cleared at the bidding area price of which they belong [20].
- **PUN Merit Orders** - They encompass the rest of the buying bids. PUN orders are a particular type of demand merit orders, in which they are cleared at the PUN price rather than the bidding area market clearing price. The PUN price is defined as the average price of the GME marginal market prices for the Italian bidding areas, weighted by the purchase quantity assigned to PUN orders in each bidding area (subject to a tolerance named PUN imbalance) [3, 16, 20].

$$P_{PUN}.\sum_{a} Q_a = \sum_{a} P_a.Q_a \pm \triangle \tag{3.3}$$

In (3.3), P_{PUN} is the PUN price, Q_a is the quantities consumed in bidding area a, P_a is the price of bidding area a and $\triangle$ is the PUN imbalance.

3.4 Algorithm

The main objective of EUPHEMIA is to maximize the SWF which is the total market value of the day-ahead auction expressed as a function of the consumer surplus, the supplier surplus, and the congestion rent including tariff rates on interconnectors. In the end, it returns the market clearing prices, the matched volumes, the net position of each bidding area, the flow through the interconnectors and the set of block, complex, merit and PUN orders that were accepted [3].

In order to solve the resulting optimization problem, EUPHEMIA runs a combinatorial optimization process structured in four different phases. First, the welfare maximization problem, referred to as Master Problem, is settled, then it solves three sub-problems, the Price Determination Sub-Problem, the PUN Search Sub-Problem and finally the Volume Indeterminacy Sub-Problem, that will be further explained in the next subsection [3].

Figure 3.7 presents a flowchart showing all four steps that constitute the general algorithm of EUPHEMIA.

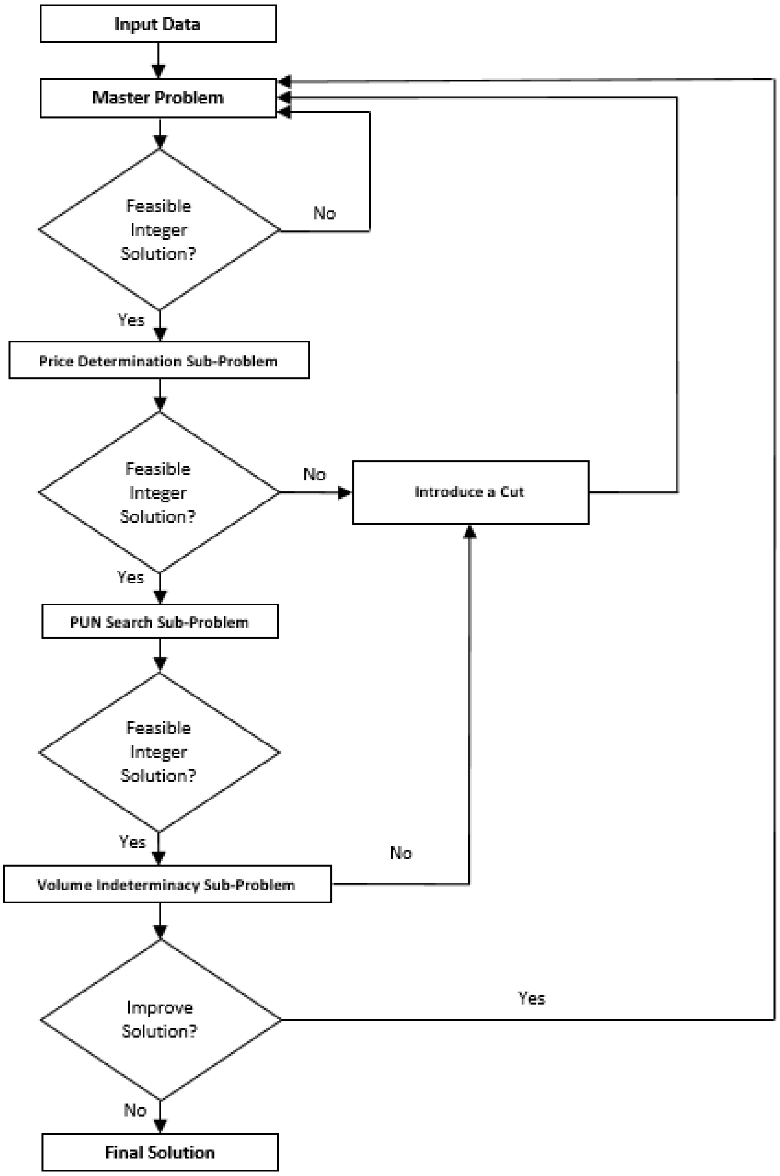

Figure 3.7: General Algorithm of the EUPHEMIA

3.4.1 Master Problem

As mentioned before, the Master Problem aims at maximizing the SWF that is calculated as the sum of the consumer surplus, the supplier surplus, and the congestion rent, which takes into account the presence of tariff rates for the flows through the interconnectors [3].

At this point, PUN orders are not enforced and EUPHEMIA searches among the set of solutions for a good selection of block and MIC orders that maximize the SWF. This problem has mixed integer nature due to the acceptance or not of block and MIC orders. Once a solution has been found, EUPHEMIA continues to the next sub-problem [3].

The results from the Master Problem should be coherent with the constraints related to acceptance criteria for the simple hourly orders, complex, merit and block orders, network constraints and flow limitations [3].

Although merit and PUN orders are not enforced in this problem, merit orders are considered as aggregated hourly orders.

The main difficulty of the master problem is to select the set of block and MIC orders that are to be accepted. The particularity of the block and MIC orders lies in the fact that they require the introduction of binary variables in order to model their acceptance (0: rejected, 1: accepted), therefore the overall problem can be modeled as a Mixed-Integer Quadratic Program (MIQP) [3].

A possible approach to solve a MIQP problem is to use the branch-and-cut method. This is an efficient method to search amongst all block and MIC selections in a structured way to prove early that large groups of these selections are not good solutions and to find feasible ones quickly [16].

Firstly, it starts without the *kill-or-fill* requirements of block orders. If the solution has no partially accepted blocks then it stops. Otherwise, if the solution happens to have fractional blocks, then it selects one of those and creates two sub-problems, which are called branches. One where the block is killed, which means it is not considered from then on, and another where the block is filled and it continues to explore until there is no unexplored branch. This technique reduces the number and range of solutions to investigate since it does not continue to explore a branch if its solution is worst than the one at hand [3, 16, 43].

The stopping criteria for this problem can be set in two ways, whether a time limit is reached or the full branch and bound tree is explored.

In case the time limit is reached, but no valid solution was found, the calculation continues until a solution is found and a second time limit applies to find the first solution. If it times out, the session fails and EUPHEMIA does not return any solution [3, 16].

3.4.2 Price Determination Sub-Problem

After finding a solution for the master problem, EUPHEMIA proceeds checking if it exists market clearing prices that are coherent with the obtained solution while satisfying market requirements [3].

The solution of this sub-problem is not straightforward because of the constraints that prevent the paradoxical acceptance of block and MIC orders and the presence of non intuitive flow based results, so infeasibility might be encountered. When infeasibility is reached, EUPHEMIA will investigate its cause and apply a cut where it is required, whether to prevent paradoxically acceptance of block orders and complex orders that do not fulfill their MIC constraint and when non intuitive results are reached regarding FB model. When there are losses in an interconnection the algorithm sends energy back and forth to take advantage of it since tariffs are applied in those cases [3].

It should be mentioned that a cut corresponds to a constraint added to the welfare maximization problem that will eliminate part of the initially considered set of feasible solutions [3].

When a feasible solution is found and market clearing prices are coherent, then EUPHEMIA shall proceed to the next sub-problem.

3.4.3 PUN Search Sub-Problem

In order to avoid Paradoxically Accepted PUN orders (PAPUN), the PUN price cannot be calculated as the average price of the marginal market prices for its bidding areas, weighted by the purchase quantity assigned to PUN orders in each bidding area while subjected to a tolerance, as mentioned before. Rather, it should be determined in an iterative process [3].

This PUN search starts as soon as a first candidate solution has been found at the end of the price determination sub-problem and the objective is to find, for each hourly period, valid PUN volumes and prices while satisfying the PUN imbalance constraint and enforcing consecutiveness of accepted PUN orders [3].

For a given period, EUPHEMIA must select the maximum PUN volume with negative imbalance, and then try to choose smaller volumes until a feasible solution is found that minimizes the PUN imbalance [3].

As soon as the PUN search is completed, EUPHEMIA checks if the obtained solution does not introduce any Paradoxically Accepted Block orders (PAB) or violates any other constraints. If some block orders become paradoxically accepted or other constrains are violated, a new cut is introduced to the Social Welfare maximization problem [3].

If the solution found for all periods of the day is compatible with the solution of the master problem, it means that the solution is found after Paradoxically Rejected MIC (PRMIC) reinsertion was performed. Otherwise, the process will resume calculating, for each period, new valid PUN volumes and prices to apply to PUN Merit orders [3].

Once the market clearing prices have been settled, EUPHEMIA proceeds with an iterative procedure aiming at checking that all the rejected complex MIC orders, that are *in-the-money*, cannot be accepted in the final solution. So, it determines the list of false PRMIC candidates and then takes each complex MIC order from this list, activates it, and re-executes the price determination sub-problem. This search is done until no false PRMIC candidate is found [3].

In the same way as PRMIC is done, Paradoxically Rejected Block orders (PRBs) are also reinserted after a fully valid solution has been found. This search helps reducing the number of PRBs, and a solution with a better welfare is quickly found [3].

At this point of the algorithm, a feasible integer selection of block and complex orders along with coherent market clearing prices for all markets have been reached and EUPHEMIA starts the next sub-problem.

3.4.4 Volume Indeterminacy Sub-Problem

After a selection of accepted simple hourly, block, complex and PUN orders and after the prices have been found providing a feasible solution to the problem, there still might be several matched volumes, net positions and flows coherent with these prices that were not acknowledged [3].

EUPHEMIA must then select one according to the volume indeterminacy rules, the curtailment rules for maximization and sharing, the merit order rules and the flow indeterminacy rules, as detailed below [3].

- **Curtailment minimization** - All orders have to be submitted within a price range in the respective bidding area. Hourly supply orders at the minimum price of the range and hourly demand orders at the maximum price of the same range are interpreted as *price-taking* orders, indicating that the member is willing to sell/buy the quantity irrespective of the market clearing price. The objective is to minimize the curtailment of these orders, which means minimizing the rejected quantity of *price-taking* orders [3].

- **Curtailment sharing** - The goal of the curtailment sharing is to homogenize the curtailment ratios between bidding areas that are in a curtailment situation and also configured to share curtailment. "A bidding area is in curtailment when the market clearing price is at the maximum or minimum allowed price for that bidding area and the submitted quantity at these extreme prices if not fully accepted." Curtailment sharing is implemented in the master problem and also in the problem of the curtailment sharing volume [3].

- **Maximizing Accepted Volumes** - By this time, the acceptance of most orders is already fixed and they are all considered to the maximization of the accepted volumes [3].

- **Merit order enforcement** - The objective is to enforce merit order numbers of the hourly orders. The acceptance of orders *at-the-money* is relaxed and re-distributed according to their acceptance priority. This step is applied only if it satisfies the PUN search sub-problem or if there are no PUN orders considered but there are still merit orders [3].

- **Flow indeterminacy** - The aim of this problem is to re-attribute flows to the ATC lines based on the linear and quadratic cost coefficients of these lines. It only affects the results when there is full price convergence in a meshed network, which allows multiple flow assignments to result in identical net positions. By changing the values of the coefficients certain routes will be chosen and the flows will be determined [3]

3.5 Summary

This chapter provides a detailed description of the EUPHEMIA regarding the market orders it supports, how the interconnections are considered, along with an explanation of the algorithm itself. Such description serves as an introduction to the next chapter since it is the base on which the simplified models were created.

Chapter 4

Simplified Model

In this chapter, two simplified models used to solve the day-ahead market are unveiled and described in detail.

Since the main purpose of this thesis is to solve the market clearing procedure in MIBEL based on EUPHEMIA, to fulfill the goal two models were created to be lately compared. The first one takes into consideration simple hourly orders whereas the second supports complex orders and their constraints, since these orders are the ones used in MIBEL. Both were compared to balance the main differences in prices and to analyze the effect of the constraints. The mathematical formulation of both simplified models is described in the subsequent subsections. whereas a more detailed formulation of a mathematical model based on EUPHEMIA is presented in [21, 44].

However, many adjustments had to be done, primarily because of the inability of finding all data required to properly achieve a seamless implementation and also because this thesis was thought to the applied to MIBEL's reality which means a few constraints and inputs were discard since were not applicable to the Iberian market.

These models were programmed in *Python* language using *Spyder*, an interactive development environment with advanced editing, interactive testing and debugging, which allowed using libraries such as *Pulp*, *Numpy* and *Matplotlib*. They are all provided by Anaconda which is a free and open source distribution of the Python language.

In order to test and validate the models, days $1/3/2016$ and $1/7/2016$ were chosen and in the second day, Market Splitting happened on hours 8 and 9.

For this purpose, the data corresponding to the supply and demand offers for each hour of the period to be analyzed was downloaded from the OMIE website [4].

4.1 Model 1 - Simple Hourly Orders

The first model created to solve the day-ahead market, takes into consideration only simple hourly orders, so any type of complex, block, merit and PUN orders, mentioned in previous chapters, were all discarded.

The transmission network was not considered, which means the problem is set only from the Market Operator point of view, where the market clearing price and quantity are determined without knowing if the dispatch would be feasible in terms of grid constraints.

Market splitting occurs in the second tested day, and this model handles it by separating markets between countries, giving different clearing prices for Portugal and Spain.

This model serves as proof of concept, because all data used was collected from OMIE website, so the results obtained for prices and quantities can be compared to the real ones. Therefore, this allows the validation of the implementation of the proposed model.

4.1.1 Mathematical Formulation

In this subsection the mathematical formulation of the model is presented, along with all indices and sets, parameters, decision variables, objective function and constraints.

Indices and Sets

t $\in T$	Set of dispatch periods in the dispatch day
d $\in D$	Set of simple hourly demand bids
s $\in S$	Set of simple hourly supply offers

Parameters

P_d^t, P_s^t	Price of simple hourly demand bid d and supply offer s in trading period t, respectively, in €/MWh
Q_d^{tmax}, Q_s^{tmax}	Maximum quantity of simple hourly demand bid d and supply offer s in trading period t, respectively, in MWh

Main Decision Variables

Q_d^t	Quantity of simple hourly demand bid d in trading period t in MWh
Q_s^t	Quantity of simple hourly supply offer s in trading period t in MWh

Social Welfare Optimization Problem

$$Max \sum_t (\sum_d P_d^t . Q_d^t - \sum_s P_s^t . Q_s^t) \tag{4.1}$$

The Social Welfare maximization in equation (4.1) comprises the total load utility minus the total offer cost of all simple hourly orders.

The Social Welfare Optimization Problem is subject to the following constraints.

$$0 \leq Q_s^t \leq Q_s^{tmax} \tag{4.2}$$

$$0 \leq Q_d^t \leq Q_d^{tmax} \tag{4.3}$$

Constraints (4.2) and (4.3) limit the maximum and minimum values accepted for the bids.

$$\sum_s Q_s^t = \sum_d Q_d^t \tag{4.4}$$

Constraint (4.4) enforces that the sum of accepted supply bids is equal to the sum of accepted demand bids.

4.1.2 Algorithm

Following the collection of orders, these are given as inputs to the problem of the Social Welfare maximization. Then, constraints (4.2) to (4.4) are applied and after it, the accepted bids as well as the Market Clearing Prices are attained.

The day-ahead market is solved when all constraints are satisfied and the solution found for the maximization of the Social Welfare is optimal.

4.1.3 Implementation and Results

In order to test the mathematical formulation and for demonstration purposes, for day 1/3/2016, a set of 31.864 simple hourly supply orders were used, along with 9.092 simple hourly demand orders comprising both bidding areas in Portugal and Spain. For day 1/7/2016 there was a set of 34.771 simple hourly supply orders and a set of 9.502 simple hourly demand orders.

Examples of the stepwise curves for hour 1 and 8 were provided in the following subsections as well as the overall results obtained with the model. These were the chosen hours to illustrate the results since in hour 1 there was no Market Splitting in any of the days and in hour 8 there was Market Splitting in day 1/7/2016.

After the mathematical problem was implemented and the inputs were provided the following results were obtained for each hour.

4.1.3.1 Day 1/3/2016 without Market Splitting

Figure 4.1, represents the aggregated stepwise curve obtained for hour 1 of day 1/3/2016, where the Market Clearing Price was 18,1 €/MWh and the traded energy was 28.654 MWh.

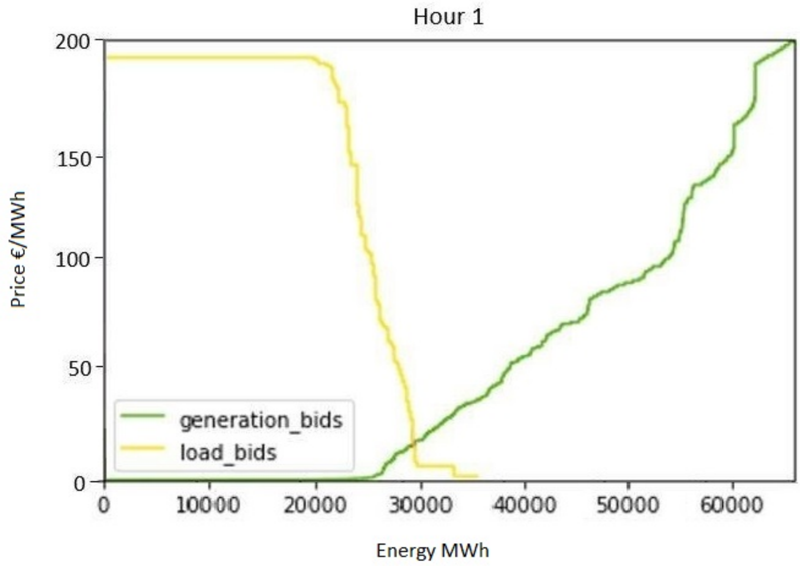

Figure 4.1: Simple Hourly Orders - Hour 1, Model 1, Day 1/3/2016

Figure 4.2, shows the aggregated stepwise curve obtained for hour 8, where the Market Clearing Price was 5,4 €/MWh and the energy dispatched was 31.847 MWh.

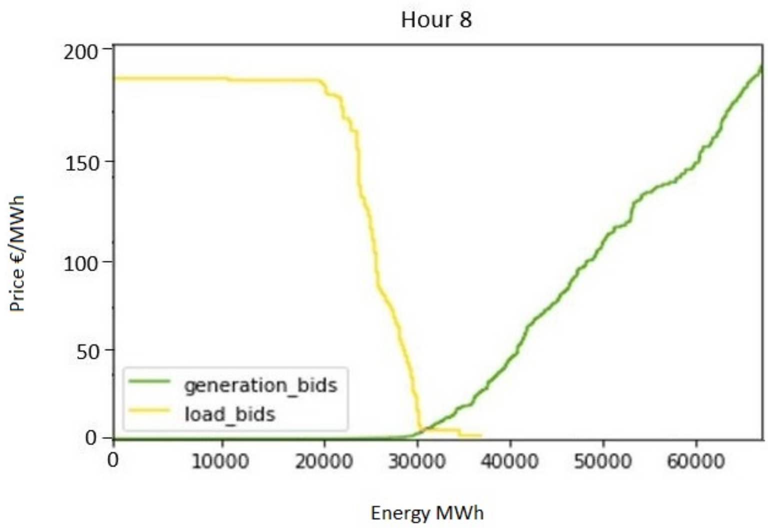

Figure 4.2: Simple Hourly Orders - Hour 8, Model 1, Day 1/3/2016

Table 4.1 shows the Market Clearing Prices and the traded energy for each hour of day 1/3/2016, along with the real prices consulted in OMIE website. It is possible to observe that the prices obtained by the model are very accurate when compared to the real ones, only small deviations were encountered.

Table 4.1: Model 1 - Market Clearing Prices and Traded Energy for day 1/3/2016

Hour	**Price (€/MWh)**	**Energy (MWh)**	**Real Price (€/MWh)**
1	18,1	28.654	18,0
2	9,05	27.002	9,0
3	5,1	25.937	5,1
4	5,0	25.459	5,0
5	5,0	25.613	5,0
6	4,9	26.249	4,9
7	4,9	28.839	4,9
8	5,4	31.847	5,4
9	5,4	34.271	5,4
10	5,0	35.847	5,0
11	5,1	37.062	5,1
12	4,0	37.628	4,0
13	4,0	37.305	4,0
14	4,0	37.112	4,0
15	2,3	36.106	2,3
16	2,3	36.256	2,3
17	2,1	34.994	2,1
18	2,3	34.177	2,3
19	2,3	35.511	2,3
20	4,0	36.918	4,0
21	5,1	38.410	5,1
22	5,0	38.009	5,0
23	4,0	35.502	4,0
24	2,3	32.486	2,3

The Social Welfare for the day-ahead market was 115.893.573,06 €.

4.1.3.2 Day 1/7/2016 with Market Splitting

In Figure 4.3, there is the aggregated stepwise curve obtained for hour 1 of day 1/7/2016, where the Market Clearing Price was 46,7 €/MWh and the traded energy was 26.730 MWh.

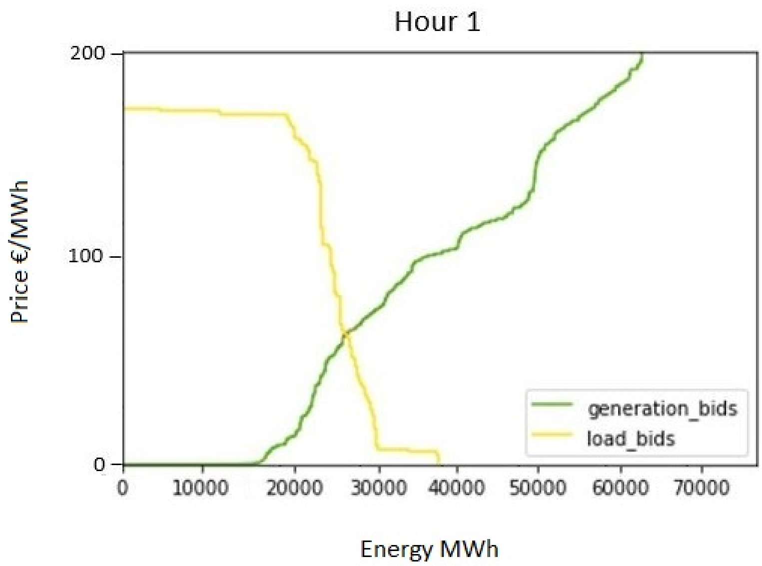

Figure 4.3: Simple Hourly Orders - Hour 1, Model 1, Day 1/7/2016

In this day, Market Splitting happened during hours 8 and 9, therefore, the day-ahead market to determine prices and quantities for those hours had to be separated for Portugal and Spain, originating the split of the Iberian Market.

Figures 4.4 and 4.5 show the aggregated stepwise curve regarding hour 8 for Portugal and Spain, respectively.

The Market Clearing Price in Portugal was 33,0 €/MWh and the traded energy was 4.983 MWh whilst in Spain the Market Clearing Price was 32,4 €/MWh and the resulted energy was 21.836 MWh. This indicates that in this hour Portugal was importing electricity from Spain and that the interconnections were at the limit on the direction from Spain to Portugal.

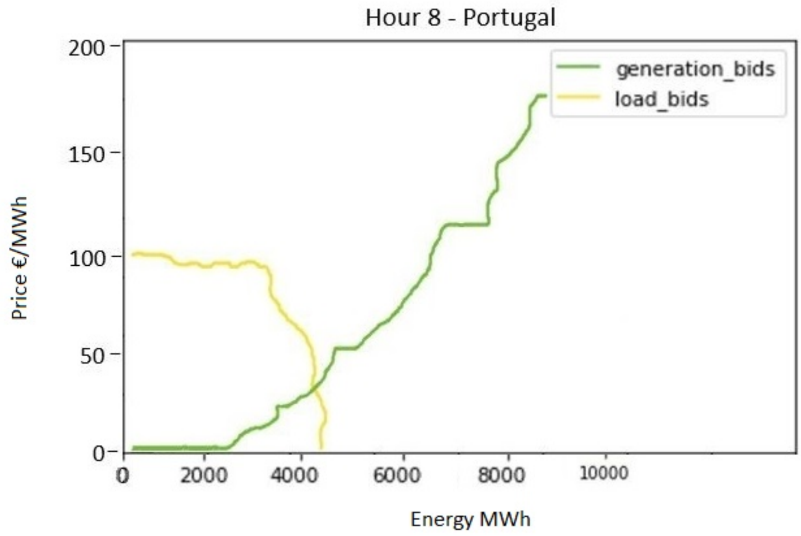

Figure 4.4: Simple Hourly Orders - Portugal, Hour 1, Model 1, Day 1/7/2016

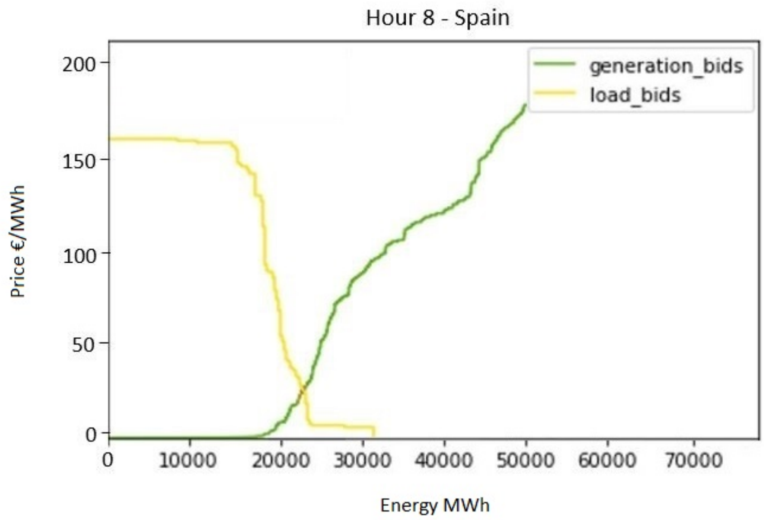

Figure 4.5: Simple Hourly Orders - Spain, Hour 1, Model 1, Day 1/7/2016

Table 4.2 shows the Market Clearing Prices as well as the attained energy for each hour of the day, along with the real prices consulted in OMIE website. Once more, as seen in the previous hour, the prices obtained by the model are very similar to the real ones.

Table 4.2: Model 1 - Market Clearing Prices for day and Traded Energy for day 1/7/2016

Hour	**Price (€/MWh)**	**Energy (MWh)**	**Real Prices (€/MWh)**
1	46,7	26.730	46,5
2	44,0	24.582	43,5
3	41,4	23.263	42,0
4	39,9	22.394	40,0
5	37,9	22.192	38,0
6	37,0	22.530	37,4
7	35,6	24.007	35,1
8	Portugal		
	33,0	4.983	34,8
	Spain		
	32,4	21.836	32,5
9	Portugal		
	33,0	6.077	33,3
	Spain		
	31,2	23.170	31,4
10	31,4	31.749	31,1
11	31,4	33.521	31,4
12	31,4	34.194	31,4
13	32,5	34.950	32,4
14	32,5	35.454	32,5
15	31,4	34.835	31,4
16	30,0	34.799	30,5
17	26,5	35.076	26,4
18	25,9	34.870	27,0
19	24,9	34.343	24,5
20	22,4	33.853	23,0
21	25,2	33.720	25,1
22	25,3	33.406	25,1
23	25,6	33.327	25,8
24	25,9	31.230	26,2

The Social Welfare for the day-ahead market was 107.162.907,96 €.

4.2 Model 2 - Simple Hourly and Complex Orders

The second developed model, can handle simple hourly orders and complex orders, since those are the ones used in MIBEL.

The transmission network was again not considered and Market Splitting is solved, as in Model 1, by separating markets between countries, giving different clearing prices for each.

4.2.1 Mathematical Formulation

The mathematical formulation of this model follows the structure in Model 1, but this time complex orders were added, more precisely load gradient constraints and minimum income condition, further explained below.

Indices and Sets

$t \in T$	Set of dispatch periods in the dispatch day
$d \in D$	Set of simple hourly demand bids
$s \in S$	Set of simple hourly supply offers

Parameters

P_d^t, P_s^t	Price of simple hourly demand bid d and supply offer s in trading period t, respectively, in €/MWh
Q_d^{tmax}, Q_s^{tmax}	Maximum quantity of simple hourly demand bid d and supply offer s in trading period t, respectively, in MWh
LG_s^{up}, LG_s^{dn}	Increase / Decrease gradient of the supply order s

Main Decision Variables

Q_d^t	Quantity of simple hourly demand bid d in trading period t in MWh
Q_s^t	Quantity of simple hourly supply offer s in trading period t in MWh

Social Welfare Optimization Problem

$$Max \sum_t (\sum_d P_d^t . Q_d^t - \sum_s P_s^t . Q_s^t) \tag{4.5}$$

The Social Welfare Optimization Problem is subject to the following constraints.

$$0 \leq Q_s^t \leq Q_s^{tmax} \tag{4.6}$$

$$0 \leq Q_d^t \leq Q_d^{tmax} \tag{4.7}$$

$$\sum_t Q_s^t = \sum_t Q_d^t \tag{4.8}$$

$$Q_s^t - Q_s^{t-1} \leq LG_s^{up} \tag{4.9}$$

$$Q_s^{t-1} - Q_s^t \leq LG_s^{dn} \tag{4.10}$$

Constraints (4.9) and (4.10) enforce Load Gradient Conditions.

$$\sum_t \lambda_t . Q_s^t \geq Rent_{min} \tag{4.11}$$

$$Rent_{min} = FT + VT.Energy \tag{4.12}$$

Constraint (4.11) is the Minimum Income Condition, in which λ_t is the marginal price for each hour and $Rent_{min}$ is given by (4.12). The last parameter, Energy, is equal to the sum of the power a given generator produced during the entire day, whereas FT and VT are the fixed and the variable generator costs provided by each producer when submitting the complex bids.

4.2.2 Algorithm

The day-ahead market is solved iteratively and not all at once. So, first, constraints (4.6) to (4.10) are applied to the problem of the social welfare maximization and then the accepted orders as well as the Market Clearing Prices are attained.

Hereafter, the Minimum Income Constraint (4.11), MIC, is added. This is a verification made to evaluate if complex orders that have MIC conditions are satisfied by the results of the market obtained in the first iteration.

If there are no violations of these last constraints, then the day-ahead market is solved and the solution obtained previously is optimal and feasible. But on the other hand, in case a MIC order is not satisfied, an iterative process begins, where the generator, whose MIC order has the biggest violated value, is removed from the Order Book and the Social Welfare Optimization Problem is again executed without considering the bids from that generator.

The violated value is calculated as below, and is the difference between both sides of the MIC equation.

$$\sum_t \lambda_t . Q_s^t - Rent_{min} \tag{4.13}$$

The day-ahead market is cleared when all constraints are satisfied and the solution found for the maximization of the social welfare is optimal.

Figure 4.6 shows a flowchart to demonstrate how the algorithm works.

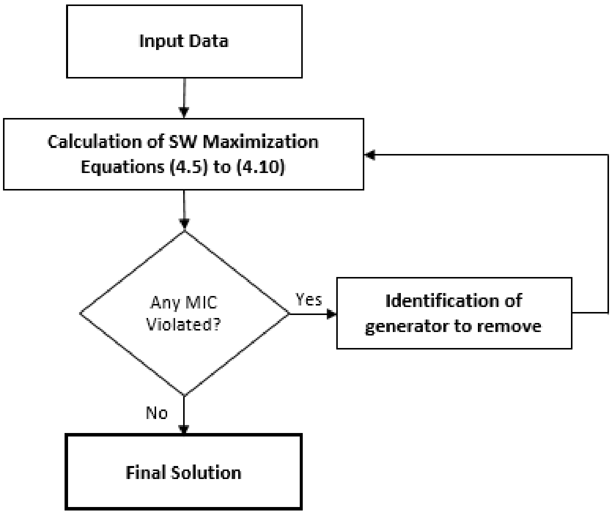

Figure 4.6: Simplified algorithm of Model 2

4.2.3 Implementation and Results

As it was previously done for Model 1, in order to test the mathematical formulation of the second model, for day 1/3/2016, a set of 31.864 simple hourly supply orders were used, out of which 200 are subjected to Minimum Income and Load Gradient Conditions (or to a combination of the aforementioned conditions), along with 9.092 simple hourly demand orders.

As for day 1/7/2016 there was a set of 34.771 simple hourly supply orders, out of which 200 are subjected to MIC and LGC complex conditions or to a combination of such, and a set of 9.502 simple hourly demand orders.

In this implementation, MIC and LGC constraints were added to simulate the conditions in which generators that were previously accepted in the first model, might not be accepted this time. This was implemented to simulate what happens in the Iberian Market regarding, for example, thermal units, since they are subjected to complexity conditions such as ramping constraints.

Examples of the stepwise curves for hour 1 and 8 were again provided in the following subsections as well as the overall results obtained with Model 2.

After the mathematical problem was implemented and the inputs were provided the following results were obtained for each hour.

4.2.3.1 Day 1/3/2016 without Market Splitting

In Figure 4.7, there is the aggregated stepwise curve obtained for hour 1, where the Market Clearing Price was 25,6 €/MWh and the attained energy was 27.634 MWh.

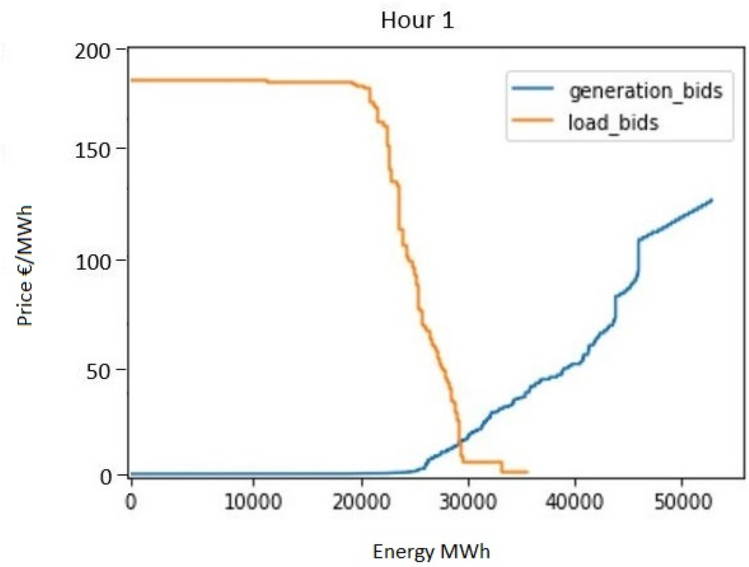

Figure 4.7: Simple Hourly and Complex Orders - Hour 1, Model 2, Day 1/3/2016

In Figure 4.8, there is the aggregated stepwise curve obtained for hour 8, where the Market Clearing Price was 31,3 €/MWh and the energy obtained was 28.130 MWh.

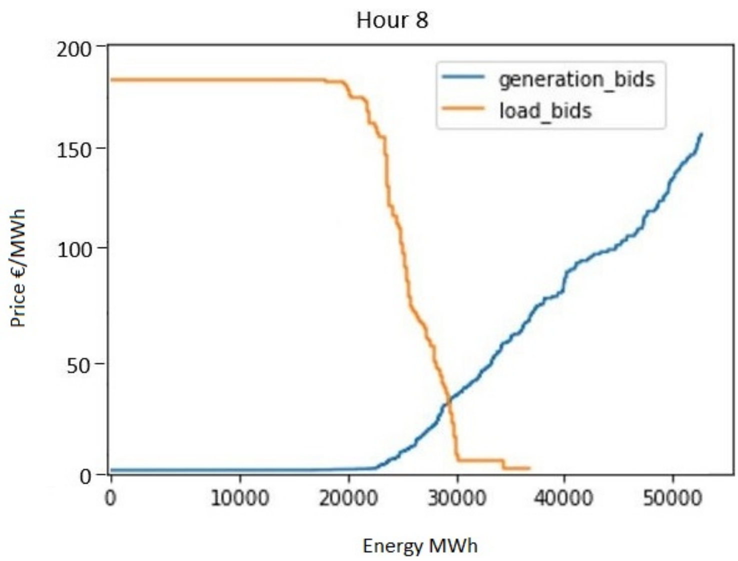

Figure 4.8: Simple Hourly and Complex Orders - Hour 8, Model 2, Day 1/3/2016

Table 4.3 shows the Market Clearing Prices and the traded energy for each hour of the day.

Table 4.3: Mode 2 - Market Clearing Prices and Traded Energy for day 1/3/2016

Hour	**Price (€/MWh)**	**Energy (MWh)**
1	25,6	27.634
2	37,8	24.456
3	24,1	23.104
4	20,7	22.443
5	22,0	22.521
6	26,1	22.712
7	18,2	27.575
8	31,3	28.130
9	24,7	31.449
10	31,8	33.002
11	32,9	33.631
12	32,6	33.784
13	32,7	33.690
14	31,5	33.515
15	28,1	32.598
16	22,0	32.472
17	20,1	33.453
18	20,0	32.193
19	29,5	31.093
20	31,4	34.169
21	21,5	36.042
22	28,0	35.169
23	21,7	32.747
24	11,3	32.406

The Social Welfare for the day-ahead market was 113.870.462,47 €.

Comparing the results in table 4.3 for Simple Hourly and Complex Bids with the ones in table 4.1 for Simple Hourly Bids, one can notice that the introduction of the complexity constraints, eliminating selling bids from the Order Book, increases the Market Clearing Price along the day. As a result, the selling curve shifts to the left side and the value of the Social Welfare function gets reduced from 115.893.573,06 €to 113.870.462,47 €.

4.2.3.2 Day 1/7/2016 with Market Splitting

In Figure 4.9, there is the aggregated stepwise curve obtained for hour 1, where the Market Clearing Price was 51,9 €/MWh and the traded energy was 26.343 MWh.

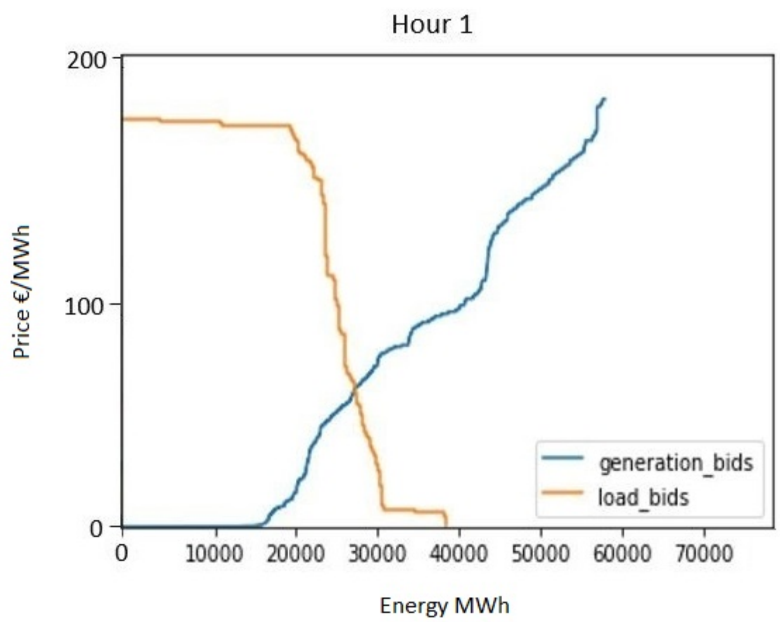

Figure 4.9: Simple Hourly and Complex Orders - Hour 1, Model 2, Day 1/7/2016

In this day there was the occurrence of Market Splitting in hours 8 and 9, therefore, the day-ahead market to determine prices and quantities for those hours had to be separated for Portugal and Spain, originating the split of the Iberian Market.

Figures 4.10 and 4.11 show the aggregated stepwise curve regarding hour 8 for Portugal and Spain, respectively.

The Market Clearing Price in Portugal was 55,7 €/MWh and the attained energy was 4.310 MWh whilst in Spain the Market Clearing Price was 56,6 €/MWh and the resulted energy was 19.501 MWh. Since the price in the Portuguese area was higher than the one in Spain, one may conclude that Portugal was importing energy.

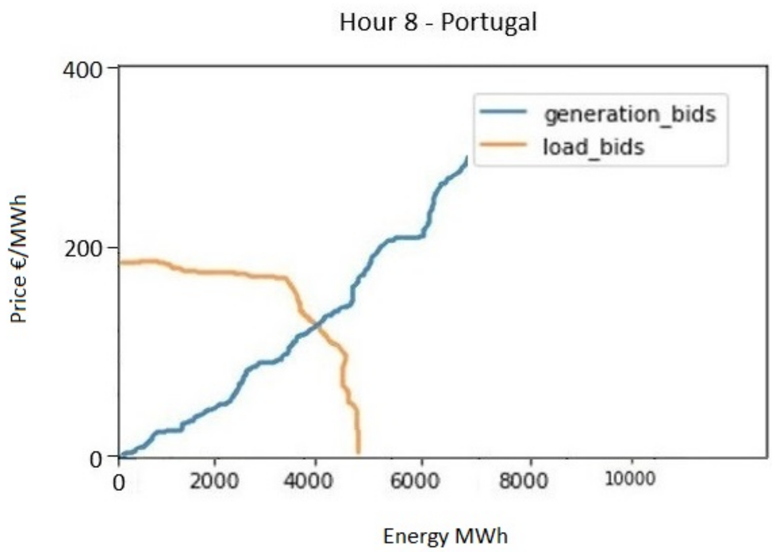

Figure 4.10: Simple Hourly and Complex Orders - Portugal, Hour 8, Model 2, Day 1/7/2016

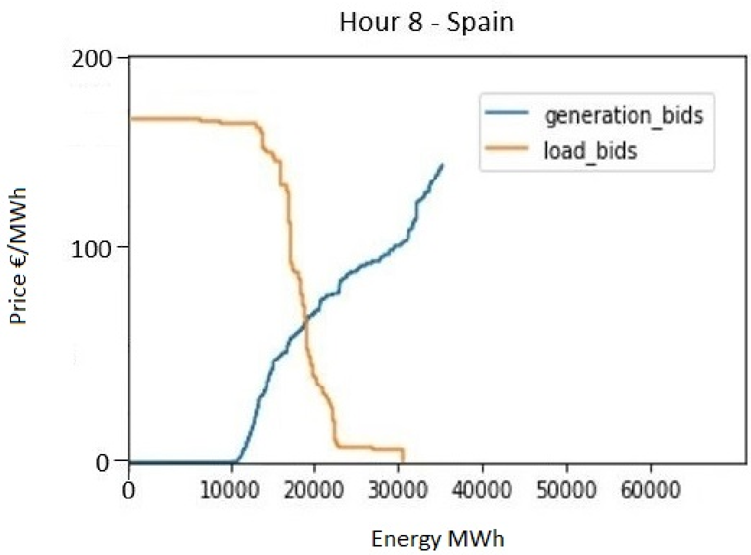

Figure 4.11: Simple Hourly and Complex Orders - Spain, Hour 8, Model 2, Day 1/7/2016

Table 4.4 shows the Market Clearing Prices as well as the attained energy for each hour of the day.

Table 4.4: Model 2 - Market Clearing Prices and Traded Energy for day 1/7/2016

<table>
<tr><th>Hour</th><th>Price (€/MWh)</th><th>Energy (MWh)</th></tr>
<tr><td>1</td><td>51,9</td><td>26.363</td></tr>
<tr><td>2</td><td>51,9</td><td>24.445</td></tr>
<tr><td>3</td><td>48,9</td><td>22.880</td></tr>
<tr><td>4</td><td>47,6</td><td>22.206</td></tr>
<tr><td>5</td><td>47,1</td><td>21.800</td></tr>
<tr><td>6</td><td>44,7</td><td>22.081</td></tr>
<tr><td>7</td><td>44,0</td><td>23.440</td></tr>
<tr><td rowspan="4">8</td><td colspan="2">Portugal</td></tr>
<tr><td>55,7</td><td>4.301</td></tr>
<tr><td colspan="2">Spain</td></tr>
<tr><td>56,6</td><td>19.501</td></tr>
<tr><td rowspan="4">9</td><td colspan="2">Portugal</td></tr>
<tr><td>56,5</td><td>3.999</td></tr>
<tr><td colspan="2">Spain</td></tr>
<tr><td>57,0</td><td>21.929</td></tr>
<tr><td>10</td><td>36,1</td><td>30.388</td></tr>
<tr><td>11</td><td>37,9</td><td>32.086</td></tr>
<tr><td>12</td><td>36,1</td><td>32.836</td></tr>
<tr><td>13</td><td>37,6</td><td>33.686</td></tr>
<tr><td>14</td><td>38,9</td><td>33.940</td></tr>
<tr><td>15</td><td>36,1</td><td>33.482</td></tr>
<tr><td>16</td><td>36,1</td><td>32.897</td></tr>
<tr><td>17</td><td>34,3</td><td>33.028</td></tr>
<tr><td>18</td><td>34,9</td><td>32.398</td></tr>
<tr><td>19</td><td>34,0</td><td>32.260</td></tr>
<tr><td>20</td><td>34,2</td><td>31.152</td></tr>
<tr><td>21</td><td>34,9</td><td>31.042</td></tr>
<tr><td>22</td><td>34,1</td><td>31.474</td></tr>
<tr><td>23</td><td>31,4</td><td>31.562</td></tr>
<tr><td>24</td><td>29,0</td><td>30.415</td></tr>
</table>

The Social Welfare for the day-ahead market was 103.572.234,91 €.

After observing the Market Clearing Prices in Table 4.4 for hours 8 and 9, one may conclude that the price is higher in Spain, which means this market was importing energy from Portugal.

4.3 Comparison between Models 1 and 2

In this subsection, a comparison between Models 1 and 2 was made in order to assess the influence of the introduction of MIC and LGC constraints in the second model. This analysis was made for day 1/3/2016 without Market Splitting.

Table 4.5, shows the prices obtained with both models for each hour of the day. It is possible to conclude that after introducing the complexity conditions, there was an increase in prices resulting from the fact that some generation units that were previously dispatched in Model 1, were not accepted in the second model because of their complexity constraints. Therefore, the selling curve shifts to the left side and as a result it is necessary to accept bids from more expensive generators to supply the demand.

Table 4.5: Comparison of Prices between Model 1 and 2 for Day 1/3/2016

Hour	Price Model 1 (€/MWh)	Price Model 2 (€/MWh)
1	18,1	25,6
2	9,05	37,8
3	5,1	24,1
4	5,0	20,7
5	5,0	22,0
6	4,9	26,1
7	4,9	18,2
8	5,4	31,3
9	5,4	24,7
10	5,0	31,8
11	5,1	32,9
12	4,0	32,6
13	4,0	32,7
14	4,0	31,5
15	2,3	28,1
16	2,3	22,0
17	2,1	20,1
18	2,3	20,0
19	2,3	29,5
20	4,0	31,4
21	5,1	21,5
22	5,0	28,0
23	4,0	21,7
24	2,3	11,3

In Figure 4.12 is shown both stepwise aggregated curves for hour 1, and as one can see there is a slight shift of the curve when complexity conditions are applied. The curve in yellow represents the load bids that did not change from Model 1 to Model 2, the aggregated supply curve from Model 1 is represented in green and in blue there is the aggregated supply curve with the complex conditions in Model 2.

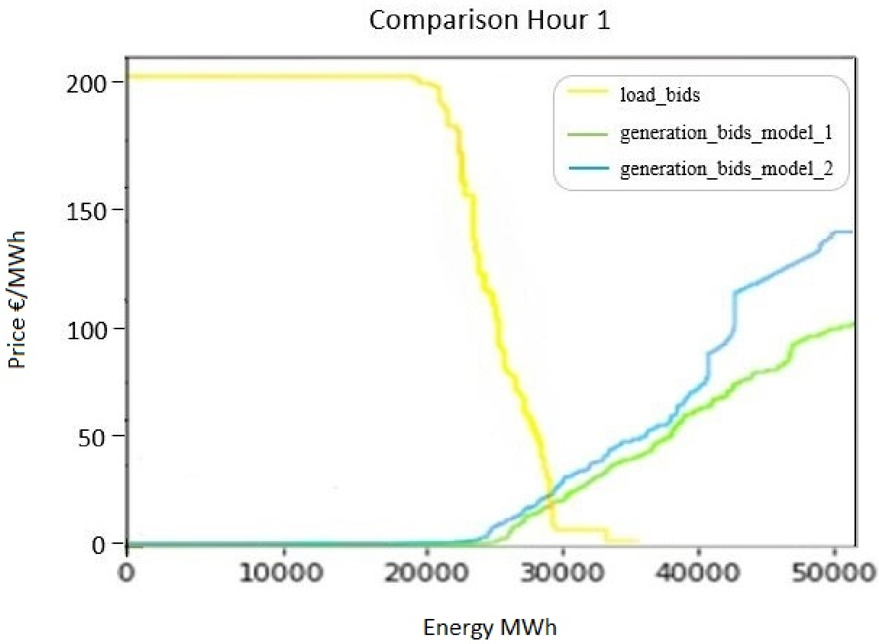

Figure 4.12: Comparison between aggregated curves for Hour 1 of Day 1/3/2016

Finally, there were also changes in the Social Welfare values for each model, presented in Table 4.6.

Table 4.6: Comparison of SW of Model 1 and 2 for Day 1/3/2016

SW Model 1	SW Model 2
115.893.573,06 €	113.870.462,47€

As expected, the Social Welfare decrease its value in Model 2. When constraints are added to an optimization problem, the value of the objective function will always get worse. In this case, since it was a maximization problem, the Social Welfare in Model 2 had to decrease.

This reflects the mentioned shift of the selling curve to the left side, thus reducing the area between the buying and the selling curves, that is the value of the SWF.

4.4 Summary

In this chapter, the simplified models were presented, together with the main drawn conclusions. With its implementation, it was possible to analyze the effects of the complexity constraints in the prices of electricity and in the value of the SWF.

Chapter 5

Conclusions and Future Work

This chapter presents the final conclusions of this work, how the proposed objectives were achieved and some drawbacks of the current implementation as well. Moreover, it describes what can be done in the future to improve the solution found.

5.1 Conclusions

The reorganization of the electricity markets along with the creation of the single price coupling solution, has increased the importance of adopting new methodologies and improving the existing techniques for solving the day-ahead market. Therefore, the creation of EUPHEMIA was an important step towards the Single European Market.

Being motivated by the fact that EUPHEMIA is a recent subject, one objective of this work was to understand its rules and procedures and to be able to implement a simplified model based on the algorithm.

Hence, the main goal of this work was to solve the day-ahead market procedure for the Iberian Market with a simplified model of EUPHEMIA.

The objectives proposed were accomplished successfully since Model 2 met the initial requirements of solving the day-ahead market for Portugal and Spain supporting simple hourly as well as complex orders, along with the constraints they require. The outputs of the model were the Market Clearing Prices and the traded Energy. Two days were tested, $1/3/2016$ and $1/7/2016$, and in the last one there was Market Splitting in hours 8 and 9.

In order to achieve the main goal, a first model was created containing only simple hourly orders serving as proof of concept since it was possible to compare these results with the real ones for each day being tested.

Then, after having a functional model with simple bids, the complexity conditions, namely MIC and LGC were added to simulate what happens in MIBEL regarding, for instance, thermal power units that have ramping constraints that must be respected.

Finally, it was possible to assess the effect of the complexity constraints in the Market Clearing Prices and overall Social Welfare. As expected, the Social Welfare decreased its value and the Market Clearing Prices suffered an increase.

5.2 Future work

Since in this thesis a simplified version of EUPHEMIA was created, the network transmission was not considered. However, taking into account the interconnections and incorporating the respective flow constraints in the initial maximization problem, as the main algorithm does, it allows solving the problem considering the activation of Market Splitting if this is necessary. Considering these flow constraints between bidding areas corresponds to the approach adopted by EUPHEMIA since the PCR project modeled the transmission system only considering the flow lines between these areas.

Given that the developed models take into account flow constraints between bidding areas, it is then possible to estimate the number of hours that Market Splitting will be activated in the future between any pair of bidding areas considering possible scenarios for generation and demand evolution. The information about this number of congestion hours can be valuable for longer term transmission system expansion planning, namely to decide future reinforcement of the interconnection capacity.

The developed model can also be of use for generation companies in order to help them evaluate the impact of different bidding strategies or to study changes on the selling curve due to the introduction of new bids eventually coming from new producers.

This work can also be useful for regulatory purposes and to policy makers in view of the fact that more than 7.000 MW out of 18.500 MW of installed capacity in Portugal is subjected to feed in tariffs. The corresponding generation estimates are included in the hourly selling curve by zero price segments and it is clear that as a result of these segments the selling curve shifts to the right reducing the market price putting out the schedule traditional thermal generators.

The developed models can then be used in order to evaluate the impact of possible increases on feed in generation (in terms of market price reductions) as well as the impact from reducing feed in generation (in terms of price increases) as some of these tariff provisions start to phase out as time goes on.

Lastly, another approach to the algorithm that is interesting for Energy Markets would be to consider ancillary services and security of reserves, therefore creating simultaneously a joint dispatch of energy and reserves in the day-ahead market in Europe.

This proposal would allow concurrent reserve capacity procurement and it would bring more stability and security to supply, along with an increase of competition in the market.

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