Electricity Market Simulator for Management of Virtual Power Plants

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Abstract

Lately, it has been witnessed a profound modification on the structure of electricity markets, with the increment in share of generation from renewable sources following the liberalization and decentralization of the market structure. In the context of this development, a technical and regulatory background has been made available for the emergence of a new figure, the virtual power plant. This acts as an aggregator of dispersed energy sources, providing access and visibility across the market.

The purpose of this study is to create a simulating tool capable of modelling the activity of a virtual power plant operating on a wholesale electricity market. This model has the MIBEL as a background and is based on estimations of electricity generation and consumption of a set of domestic producers. Generation data is obtained from the application of the three parameter model on inputs of temperature and solar irradiance from weather forecasts while consumption data is provided by the SmartGalp experience. The simulator computes values for the energy balances for each hour and obtains the market revenues from the sale on the Iberian daily market, OMEL. Simulation runs are performed on distinct initial parameters to assess the ideal operation of the virtual power plant.

Considering the general simplicity of the model compared to the activity of a real electricity market, it was possible to conclude that the simulator is able to project the operation of a virtual power plant, as it successfully emulated the expected results for the set of different initial conditions.

Keywords: virtual power plant, simulator, electrical energy, electricity market, renewable energy.

Resumo

Ultimamente tem-se observado uma profunda alteração na estrutura dos mercados de electricidade, com a crescente aposta na produção a partir de recursos renováveis, acompanhando a liberalização e descentralização do sector. Este desenvolvimento tem propiciado o aparecimento de um ambiente técnico e regulatório favorável ao aparecimento de um novo agente no mercado, a central de geração virtual. Esta figura actuará como um agregador de recursos dispersos, proporcionando melhor visibilidade e condições no acesso ao mercado.

Com este projecto pretende-se construir uma ferramenta de simulação capaz de modelar a actividade de uma central de geração virtual a operar no mercado grossista de electricidade. Este modelo terá como fundo o MIBEL e será baseado em estimativas de produção e consumo de energia eléctrica para um conjunto de produtores domésticos. Os valores de produção serão obtidos pela aplicação do modelo de três parâmetros sobre dados de temperatura e irradiância solar provenientes de previsões meteorológicas e os dados de consumo serão cedidos pela experiência SmartGalp. O simulador calcula os valores da energia disponível para cada hora e determina as receitas provenientes da venda no mercado Ibérico diário, OMEL. As simulações são executadas segundo conjuntos de parâmetros iniciais distintos de forma a avaliar as condições óptimas de operação da central de geração virtual.

Considerando a simplicidade do modelo face ao funcionamento real de um mercado de electricidade, pode concluir-se que o simulador permite a modelação eficaz da operação de uma central virtual, tendo sido obtidos os resultados esperados para os distintos pressupostos assumidos.

Palavras-chave: centrais de geração virtual, simulador, energia eléctrica, mercado de electricidade, energias renováveis.

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List of Abbreviations

DER – Distributed Energy Resources

EC – European Commision

ERSE – Entidade Reguladora dos Serviços Energéticos

EU – European Union

IEA – International Energy Agency

MIBEL – Iberian Market for Electricity

OECD – Organisation for Economic Co-Operation and Development

OMEL – Spanish Division of the Iberian Market Electricity Operator

OMI – Iberian Electricity Market Operator

OMIClear – Clearing House for the Iberian Electricity Market

OMIP – Portuguese Division of the Iberian Market Electricity Operator

PV – Photovoltaic

REE – Red Eléctrica de España

REN – Redes Energéticas Nacionais

VPP – Virtual Power Plants

1 Introduction

1.1 Motivation

Over the last years, it has been witnessed a profound modification on the structure of markets for electricity. These have been moving from a model where monopolistic companies had control over all production, transmission and distribution activities, to a gradually more competitive and decentralized organization. The economic efficiency derived from the introduction of competition in the sector has the ultimate goal of benefiting consumers and so, the regulatory and legal frameworks have adapted in order to stimulate the liberalization of the electric system [1].

The use of renewable energy technologies is one of the most debated issues in the energy field in the present day. The growing concerns with the environment's degradation and the health issues arising from that situation have encouraged the investigation in clean energy sources. The continuous evolution of technology has allowed for significant advances in alternative electricity generation processes, such as photovoltaic, wind and biomass. Due to these factors, the share of electrical energy produced from renewable sources has been steadily increasing, especially at the mini and micro-generation levels [2].

In the context of these two realities, a technical, regulatory and market background has been created for the emergence of a new figure, the Virtual Power Plant (VPP). This agent will work as an aggregator of dispersed energetic resources, providing visibility and access across the market. By removing the uncertainty factor related with production from renewable sources, through the correct balancing of a portfolio of different generators, VPPs could play an important role in the further incorporation of clean energy sources in the generation of electricity [3].

Through this work, it is expected to be obtained a better understanding of the conditions in which VPPs ideally perform as a single electricity producer, by simulating their strategic approach in a contextualized market for electrical energy, under the current Portuguese regulatory framework.

1.2 Objectives

The specified aims of this thesis are:

1. Development of an electricity market modelling tool, comprising the current technical, regulatory and market framework;
2. Test and assess the market participation of VPPs in the simulated environment in order to maximize benefits for producers and consumers;
3. Evaluate the model and conclude on the viability for use as a market result prediction tool for VPP operators.

1.3 Structure of the thesis

The thesis is structured in seven main chapters.

On chapter 1, it is introduced the developed work, pointing motivation and objectives to be attained. A topic overview is also presented

On chapter 2, it is presented a revision of the literature on some important subjects related with this thesis, namely electricity markets in general, the Iberian market for electrical energy (MIBEL), the regulatory framework and the Virtual Power Plants.

On chapter 3, it is presented a review on the existing simulation models.

On chapter 4, it is described the construction and implementation of the simulator built in the purpose of this work.

On chapter 5, the results of this work are seen and an analysis on the different strategies of the Virtual Power Plants will be performed, as well as on the simulated mode itself.

Finally, on chapter 6 the conclusions arising from the development of this work are exhibited and some acknowledgments for future studies are made.

1.4 Context and background

1.4.1 Understanding electrical energy

Electricity is a basic necessity for the development of any economic activity and thus, it has been increasingly treated as a commodity in the modern energy trade systems, becoming a ground principle in the evolution of electricity markets. However, several important differences separate electrical energy from other commodities like oil, cereals or metals, causing significant impact on the structure and legislation of electricity trade organizations.

The most noteworthy difference is the fact that electricity is bound to a physical infrastructure, including power plants, transmission lines and distribution networks, through which it circulates under the laws of physics, much faster than the functioning of any market. Because of that, and above all contractual obligations, a balance must be achieved at all times between generation and load. If the system is unable to maintain this balance, it will collapse with disastrous social and economic consequences.

Another ground feature of this commodity is its unpractical storability, given the current state of technology. It's not economically and logistically viable to store large quantities of electrical energy except through the use of large hydro power plants, and so, it must be produced virtually at the same time it is consumed. Therefore, when electricity is traded, there's always a reference to the time period in which it is delivered, resulting in a distinction of electrical energy supplied in different periods, with corresponding different prices.

An additional characteristic of electricity is the fact that the energy generated by one producer is indistinguishable from the energy produced by others. Furthermore, because of its physical nature, it is impossible to specifically direct electricity from one generator to one consumer. Instead, all power produced is centrally pooled on its way to supply the loads, resulting in significant economies of scale. Since the system is linked in a centralized way, a breakdown somewhere along the structure would affect every agent and not just the party responsible for the rupture.

Lastly, as in other commodities, the demand for electricity varies cyclically during a day or a week. However, unlike other goods, and since it has to be produced as it is consumed, electrical energy must be generated by production facilities capable of responding to the changes in consumption. In contrast to coffee or cereals, which are produced through a specific process and then stored to respond to peaks in demand, distinct generation plants produce power during a day. During low demand periods, only the more efficient plants are able to produce, while some other units are only needed during load peaks, due to their less efficient way of running but faster responding time [4].

All these distinctive characteristics make electricity different from any other commodity, but as we will have the opportunity to see, they have been taken into account during the development of electric energy trade systems throughout the history.

1.4.2 Worldwide electricity generation

After discussing some of the features that make electrical energy into a distinct kind of commodity, it will now be presented a general view of the production of electricity worldwide, with a focus on the progress of the share of renewable generation.

Looking back on the evolution of electricity generation by source over the past 40 years, it becomes obvious that fossil fuels have always had a major share, maintaining at present time a portion of around two thirds of all the power produced worldwide. However, there has been a restructure in the composition of the portion of fossil thermal fuels, as the natural gas has risen from 12.2% in 1973 to 21.9% in 2011, while the oil portion has evolved in the opposite direction, lowering from 24.6% to 4.8%. The most important component is still coal, which has maintained a steady growing trajectory, totaling in 2011 for 41.3% of electricity generation worldwide [5]. This solid share is due to the relative low price of coal, when compared to other raw materials used in conventional thermal processes and its availability in all geographies in the world (unlike oil or gas). Nonetheless, in some countries, for instance the U.S.A., natural gas prices have been low enough for energy companies to start operating natural gas powered generation plants more economically than coal plants, mostly through the use of hale gas [6]. On the other hand fast growing countries, such as India and China have based the supply of their rising electricity needs in “cheap” coal-fired power plants. In fact, coal based generation in China represents around 45% of the total worldwide coal-fired power production. These opposing phenomena have resulted in a steady growth in the coal share of produced electricity.

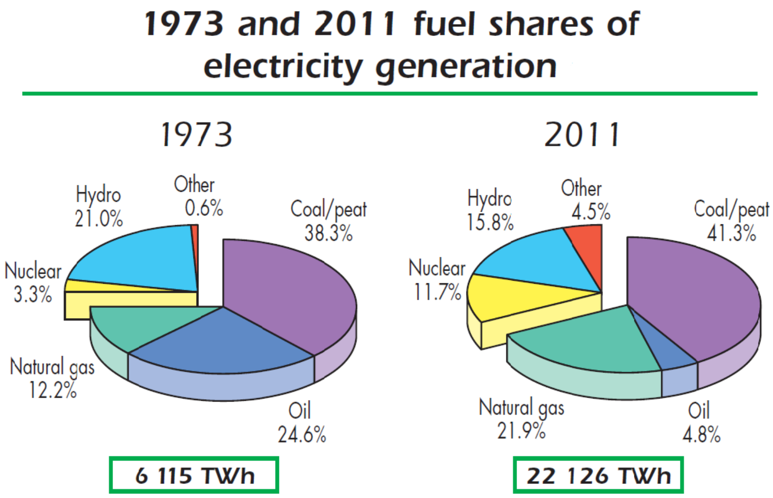

Figure 1.1: Generation by fuel, 1973 to 2011. Other includes geothermal, wind, solar and biomass [5].

In Figure 1.1, adding to the information on fossil fuel shares, it is also noticeable the rise in the percentage of nuclear powered electricity production, mainly due to the policies followed in OECD countries over the last decades. In France, the contribution of nuclear production in total domestic power generation accounts for more than 79%.

1.4.3 Renewable generation

In respect to renewable sources of electricity, the 21.6% share in 1973 has lowered to 20.3% in 2011, with hydro representing the major portion in this sector. However, when looking at this data, it must be taken into account the growth in total electricity generated which has risen almost four times since the first period considered. Hydro power production, strongly dependent on natural conditions, such as substantial storability of water, has evolved at a steady pace, with the appearance of some particular examples. Countries like Brazil or Venezuela obtained in 2011, 80.6% and 68.6%, respectively, of their total domestic generation from hydro power plants, and Norway managed to produce 95.3% of its electricity through this source [5].

Since this work will focus on non-dispatchable renewable energy resources, more specifically on solar photo-voltaic (PV), as integrating parts of Virtual Power Plants, it is of special interest to understand the evolution of these sorts of generation sources in the last decades. Also, it is important to get acquainted with the different estimations of development of the renewable sector, according to key institutions such as the International Energy Agency (IEA) [7] or the European Commission (EC) [8].

As it can be observed in Figure 1.1, the share of non-hydro renewable technologies increased by significant amount from a mere 0.6% of the total world generated electricity in 1973 to 4.5% in 2011. Most of this improvement has been achieved in the last decade, supported by the numerous incentives and support schemes existing in the European Union, U.S.A. and other important agents to enlarge the share of renewables in the generation mix. Increasing worries with the environment's degradation due to excessive CO_2 emission to the atmosphere and the unstable prices of fossil fuels have created a sense of necessity to the rapid expansion witnessed in the sector. Also, the evolution in technology with the subsequent production cost reduction have made possible for some renewable solutions to be economically competitive with fossil fuel technologies, providing the financial incentive to invest in projects for renewable energies.

In the United States, a set of stimulus policies directed at the market for renewables, in the form of cash grants for selected projects or tax credits for investment and production, has promoted a strong growth in the industry. In addition, nationwide goals for the introduction of renewable sources, such as the Renewable Portfolio Standards (RPS) are believed to maintain incentive to keep the deployment of these projects.

In non-OECD countries, for instance China and India, the fast growing demand for electricity combined with concerns over local pollution and energy security have boost the implementation of renewable energy projects. Ambitious plans set goals for the integration of new renewable generation capacity in the grid by the end of the decade. In South Africa, Morocco and United Arab Emirates, countries with exceptional natural conditions, are analyzing investments in solar PV, wind and concentrating solar power (CSP) at a large scale for deployment in a near future [7].

In Europe, the Renewable Energy Directive 2009/28/EC established an agenda for the promotion of renewable energy, with the setting of national targets and plans. These targets are to be combined in order to obtain a global goal of 20% share of renewables in final energy consumption in the European Union by the year 2020.

Member State	2005 RES share	2010 RES share	1st interim target	2020 RES target
Austria	23.3%	30.1%	25.4%	34%
Belgium	2.2%	5.4%	4.4%	13%
Bulgaria	9.4%	13.8%	10.7%	16%
Cyprus	2.9%	5.7%	4.9%	13%
Czech Republic	6.1%	9.4%	7.5%	13%
Germany	5.8%	11.0%	8.2%	18%
Denmark	17%	22.2%	19.6%	30%
Estonia	18%	24.3%	19.4%	25%
Greece	6.9%	9.7%	9.1%	18%
Spain	8.7%	13.8%	10.9%	20%
Finland	28.5%	33%	30.4%	38%
France	10.3%	13.5%	12.8%	23%
Hungary	4.3%	8.8%	6.0%	13%
Ireland	3.1%	5.8%	5.7%	16%
Italy	5.2%	10.4%	7.6%	17%
Lithuania	15%	19.7%	16.6%	23%
Luxembourg	0.9%	3%	2.9%	11%
Latvia	32.6%	32.6%	34.0%	40%
Malta	0%	0.4%	2.0%	10%
Netherlands	2.4%	3.8%	4.7%	14%
Poland	7.2%	9.5%	8.8%	15%
Portugal	20.5%	24.6%	22.6%	31%
Romania	17.8%	23.6%	19.0%	24%
Sweden	39.8%	49.1%	41.6%	49%
Slovenia	16.0%	19.9%	17.8%	25%
Slovakia	6.7%	9.8%	8.2%	14%
UK	1.3%	3.3%	4.0%	15%
EU	8.5%	**12.7%**	**10.7%**	**20%**

Figure 1.2: Member States' progress in comprising with the "Energy Directive [8].

In Figure 1.2, we can see in a red highlight, countries that, in 2010, fall more than 1% behind their first interim target. In a yellow highlight, there are those who are between 1% behind and less than 2% ahead of their first interim target. Finally, in green, it can be seen the case of those which, by 2010, are more than 2% ahead of their goal for the 1st interim target, which corresponds to the average combined target for 2011/2012.

Due to the fact that this project will have the MIBEL as a background for developing a simulator for a market of electrical energy, it is important to understand the recent state of implementation of renewable technology in both Portugal and Spain. In a yellow highlight, Portugal presents in 2010, 24.6% of renewable energy share (RES), above the 22.6% target for 2011/2012, but still below the objective for 2020, of 31%. Portugal has set an ambitious goal, well above the 20% target for EU in general, which has been equaled by Spain as its goal for 2020. In 2010, Spain had reached 13.8% of RES.

As it can be seen in Figure 1.2, the majority of the Member States presented a large growth between their 2005 and 2010 results. This acts as an effect of the subsidy policy which boosted projects in renewable energy solutions. The weak economic situation and a slow demand growth have however raised doubts about the sustainability of this level of incentives all around Europe. In fact, the overuse of the available support systems and the significant reduction in solar PV system costs led some countries to adjust their financial aid schemes to a more affordable level. The higher than anticipated share of renewables, besides creating some economic instability also caused difficulties in terms of integrating high levels of variable and uncertain sources of energy into the electric system. Despite the need to adjust transmission and distribution systems to accommodate the introduction of large rates of renewable sources, the EU seems to be on the way to reach the 20% target for 2020.

1.4.4 Solar photo-voltaic (PV)

The already mentioned cost reductions in technology were greatly felt in this area, with the introduction of new solutions, such as thin film technologies, and the opening of the western markets to the economically competitive products coming mainly from China. Combined with this trend, government support programs to renewable generation practiced in many countries drove solar PV generation to increase by 50% over the last decade. In fact, in 2012, the global installed capacity of solar PV expanded by 43%, totaling for 15% of the overall increase in power generation capacity [7].

According to the IEA, electricity generated from solar PV is supposed to rise up to 950 TWh in 2035, from the 100 TWh produced in 2012. This estimation is aligned with a projected future setting in the energy sector, called New Policies Scenario [7]. In this outlook, it is expected a broad policy commitment at international level, as well as national strategy plans to reduce greenhouse-gas emissions and the dependence on fossil fuels. It is regarded as the baseline for future projections on energy issues, assuming a growing agreement on the need for a cleaner power generation sector.

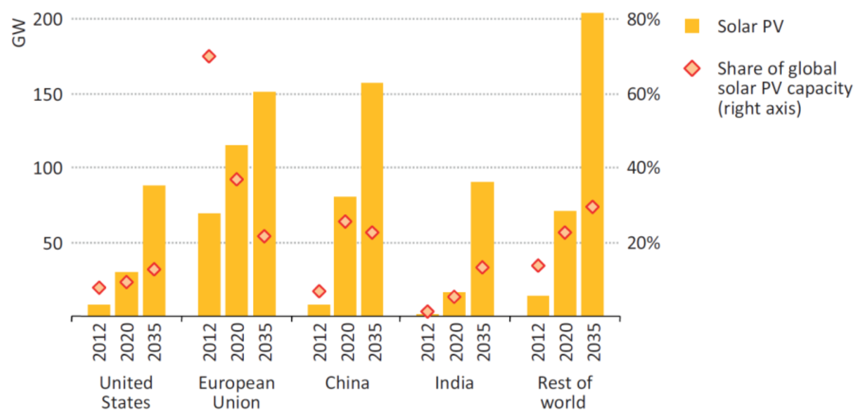

Figure 1.3: Projected solar PV capacity by region in the New Policies Scenario [7].

In this projection, large developments in solar PV generation capacity are to occur, especially in China, India and other countries, while the EU and United States seem to be already in a more mature phase into the process.

The EU presented in 2012 a share of around 70% of the total installed capacity, which confirms the presence of a strong set of directive policies around Europe. However, it also indicates the existence of a large growth potential as many regions of the world are virtually insignificant in terms of solar PV installed capacity and are now starting to alter their positions. In 2035, despite an increase of 100% in EU's generation capacity, the share in the worldwide total is expected to lower to around 20%.

2 Topic Overview

2.1 Electricity markets

2.1.1 Background and evolution of electricity markets

For many years, consumers didn't have a choice when they wanted to buy electrical energy. Since the supply of electricity was mostly held by vertically integrated utilities, controlling generation, transport and distribution, clients were bound to purchase energy from the company that managed said activity in the area they were located. In different regions, some of these utilities were private companies and others were government agencies [4].

This type of operational model made important contributions to the world we know today, both at the level of global economic activity and at improving quality of life, based on regular technological advances. Nowadays, the average consumer of electricity in the developed countries is deprived of electrical energy for very short periods only. Also, there are increasingly less business activities that don't benefit from the use of electricity.

Despite having played an important part in the evolution of civilization, there came a time when some people started claiming that the monopolistic model of electric utilities had become out-dated. During the decade of 1980, groups of economists started to defend that vertically integrated utilities were removed from the incentive to operate efficiently, incurring in unnecessary investments that were passed on to the consumers. Some public companies were used for profit reasons while others were impeded from practicing tariffs that reflected production costs. These experts proposed the introduction of a market discipline in the electricity trade, stating that it would bring economic benefits. Competition arising from the deregulation of electricity markets would motivate efficient behaviour from all the agents involved, in search of lower costs. Competing companies would probably resort to different technologies, with corresponding levels of price and reliability, benefiting the consumer with the possibility of choosing an electricity supplier suitable to its needs.

Since then, electricity markets in various regions have moved away at different rates from vertically integrated utilities to a liberalized market. With the gradual appearance of independent power producers, monopolistic companies were no longer the only generators of electricity and generation companies started to emerge. Then the distribution companies came, which purchased directly from the power producers the energy their clients consumed. The continuous division of the electrical value chain, with the separation of generation, transmission and distribution led to the disaggregation of local monopolies, with the introduction of the retail competition model. In this model, generation companies compete to produce electricity, which they sell to retailers or large consumers in a wholesale market. Retailers then compete to offer the best price to small consumers in the retail market. According to this model, the only monopoly that will remain in activity will be the one related with the provision and operation of distribution and transmission network [1].

This would be the definitive form of a deregulated market for electricity as it would work in the consumers best interest, making possible for them to choose their supplier.

2.1.2 Trading and balancing electrical energy

Regarding the operation of a liberalized electricity market, the transaction of electrical energy can happen by two different open trade systems.

There are the bilateral contracts involving only two parties, a buyer and a seller. In this type of trade, the amount of energy contracted, the period in which it is delivered and the agreed price are set between the two agents involved, with no interaction from a third party. There can be found several forms of bilateral trading, according to variations in the terms mentioned above. There are long-term contracts, through which are traded large amounts of power over long time periods with some level of flexibility in order to meet the needs of both parties. In addition to these, there are also “over the counter” trading agreements, involving smaller quantities of electrical energy over a shorter period of time. Finally, electricity trading can be done electronically between two parties, through a computerized marketplace. In this method, buyers and sellers anonymously introduce their offers and bids for delivery in a specific time period, and wait for a match to occur. All these forms of bilateral trading have in common the fact that the price is decided independently between the two parties involved, and so, there is no standard price for electricity, which represents a considerable leap from the conventional practice.

The other trading mechanism for electrical energy is the electricity pool, depicted in Figure 2.1. In this system, as the power produced by generation companies is centralized on its way to supply the load for a specific period, bids made by producers and offers made by consumers are introduced in a pool. Then, bids to produce are ranked in order of increasing price while offers to buy are ranked in order of decreasing price. This information will form the supply and demand curves of the market, respectively. The intersection of these two curves will give out the market equilibrium with the determination of the traded quantity and clearing price. Any bid equal or below the clearing price and any offer above or equal to this value will be accepted. The system marginal price found at the equilibrium will be the same for all the transactions, encouraging generators to bid a price that reflects their marginal production costs.

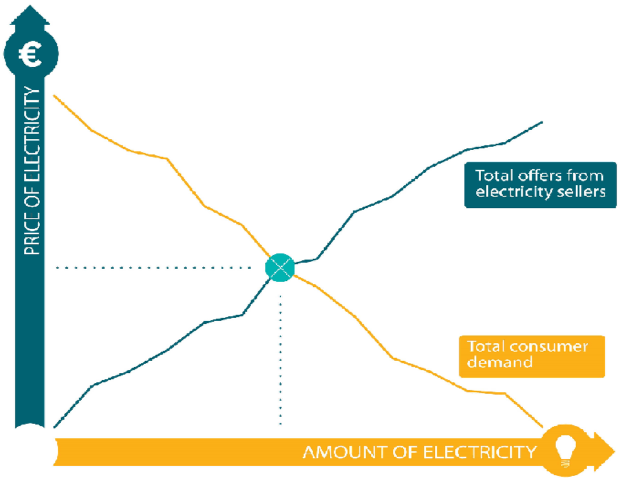

Figure 2.1: Illustration of a pool mechanism [9].

Whether the electrical energy transactions are made through bilateral contracts or resorting to a pool mechanism, the goal of the interactions between buyers and sellers is to produce a state of equilibrium between supply and demand. Balancing generation and load is not always possible through these types of trading mechanisms. Both clients and producers make efforts to accurately forecast their consumption needs and production outcomes, in order to better estimate how much to purchase or bid, respectively. However, the verified demand of a group of consumers rarely matches the forecasted value. In addition, unpredictable problems may prevent generation units from delivering the contracted power outcome. These setbacks introduce imbalances in the equilibrium between generation and load that must be corrected on time, with the aim of preventing ruptures in the system. For that, there is the spot market, in which buyers and sellers are able to rectify their deficits or excesses of contracted power, with possible financial losses due to variations in the spot price for electricity. In this last resort market, power is offered by the participants with a price of their own choosing that reflects the cost of production of different technologies as well as the evolution in the estimates of both production and consumption sides. Contrasting with other commodities, like cereals or coffee, in which the goods sold at the spot market are produced in the same means, the electricity sold at this market is usually produced by the most flexible generators. A few power plants that have faster start-up times and probably higher production costs occupy this market position, and usually are not able to compete to the supply of the bulk of the electrical energy traded.

In spite of the vulnerability to fluctuations in the price of electricity in this last resort market, which may result in unexpected high expenditures, participants do have an alternative to rectify their contractual obligations. The spot market provides a mechanism to balance generation and load and thus, its operation should rectify the open trade market as the time of delivery approaches. With a fair and efficient last resort market, electricity could be traded like any other commodity [1].

2.2 Iberian Market for electricity – MIBEL

After having looked at the main features of electrical energy as a commodity and introduced the basic principles behind the functioning of electricity markets, it will be presented now the Iberian market for electricity, the closest example of a power trading mechanism and part of an effort of European market integration.

2.2.1 MIBEL – Constitution and objectives

The Iberian Electricity Market (MIBEL) is the outcome of a joint effort from both the Portuguese and Spanish Governments to the integration of the electrical systems of the two countries. The materialization of MIBEL greatly contributed to the establishment of an electricity market at the Iberian level but also at European level as a significant step towards the integration of an Internal Energy Market.

Within this new reality, it became possible for any consumer in Portugal or Spain to purchase electricity from any retailer or producer in the Iberian Peninsula, under an openly competitive regime, improving transparency and promoting the cooperative development of the electricity value chain in both countries. Under this condition of equality and objectivity, the existence of a single reference price for electricity in the whole region, contributed to the economic efficiency of electric utilities, through the stimulation of free competition.

Formally, the conjunction of the electrical systems between the two countries was initiated in 2001, with the signing of the "Protocol for collaboration between the Portuguese and Spanish Administrations for the formation of an Iberian Electricity Market". The grounds needed to initiate cooperation between regulators, infrastructure's administrators and other important entities were set in that document. Later, in October 2002, it was decided the organizational model for MIBEL, as it was to be based on the existence of the Iberian Market Operator (OMI). A solid physical infrastructure was to be created to enable the articulation of power transmission networks. Also, the legal and regulatory frameworks were to be adjusted, as well as the economic conditions of market participation, in order to harmonize the systems operational procedures. The Iberian market would embody an intermediary regional approach of the integration of national electricity markets into a single European market. In this summit, both Governments agreed that the organized markets of MIBEL would be based on a communicating bipolar structure, in which the management of the day and intraday market would be under the control of the Spanish division (OMEL) and the derivatives market would be at the Portuguese (OMIP) division's responsibility.

In Lisbon, in 2004, it was signed the "Agreement between the Portuguese Republic and the Kingdom of Spain for the Constitution of an Iberian Electrical Energy Market". The most noteworthy aspect of this agreement was the reciprocal recognition of agents, meaning that any agent that was granted the status of producer, marketer or other by one country would be promptly recognized by the other country. This feature would promote equality of rights and obligations in all Iberian territory.

On July 2007, after overcoming delays in the implementation of the legal and regulatory framework due to political instabilities, MIBEL was fully launched as it drove to a successful conclusion the agreement of requirements between the two electricity systems. Expectations were that benefits would be brought to the consumers with the possibility of participating in a transparent and competitive market for electrical energy [10].

2.2.2 Day-ahead and intraday markets - OMEL

The Spanish division of the Iberian Electricity Market Operator (OMEL), headed in Madrid, is responsible for managing the functioning of the pool market for electricity in this bipolar structure. This last resort market is based on the operation of the day-ahead and intraday trading mechanisms that aggregate the Portuguese and Spanish zones of MIBEL.

The day-ahead market, as part of the wholesale electricity market, is meant to handle electrical energy transactions for delivery on the following day. Agents from the entire Iberian region take part in a daily auction in which they introduce bids and offers for the trade of energy for every hour. All production units not bound by bilateral contracts must get involved in this market, as well as other agents registered as supplying entities. On the buying side there are the retailers and large consumers but also generating entities looking for a last resort supply [11].

Electrical energy transaction orders are presented to the system operator, which will include them in a pool mechanism, initiating a matching procedure that will find the equilibrium price and quantities. There are twenty-four programming schedules set through this process, with the deadline time for the reception of bids and offers being at 10:00h of the day previous to the delivery. Most transaction orders are simple, including only a specified price and amount of electrical energy, but others may include more complex sales terms and conditions.

Being a simple and immediate market, in which consumers and producers are able to trade the exact amounts they wish, the day-ahead market is prone to produce quick and unpredictable changes in the price of electrical energy. The interaction between buyers and sellers to produce the price is a source of variability itself, since the generation and load may vary for the same period on different days. Additionally, sudden drops in the predicted production or increases in demand may induce unexpected rises in the price of electricity, as the stock of goods may be limited for the delivery at a certain hour. Moreover, the day-ahead market price is also influenced by information related to weather forecasts, since an important share of generation comes from renewables. The availability and price of concurrent commodities, like coal or oil has an effect on daily electricity prices as well. This vulnerability both to inside and outside fluctuations makes the day-ahead market price slightly unpredictable, which introduces a significant amount of risk in this sector. Producers will try to avoid selling at a low value, while consumers usually set a maximum limit for the price they are willing to pay for electrical energy.

To tackle with the risk linked to the day-ahead price, and serving as a response to adjustments made to the final daily schedules, there is the intraday market. This section of MIBEL represents the last opportunity for market agents to balance contractual positions, operating between the day-ahead market and the gate closure for transactions.

Sharing the process basis of the daily market, with generators and purchasers specifying the price and amount of energy they wish to trade, the intraday market consists of six auction sessions with different time extent coverage for a common day, providing a balancing mechanism for market agents in need.

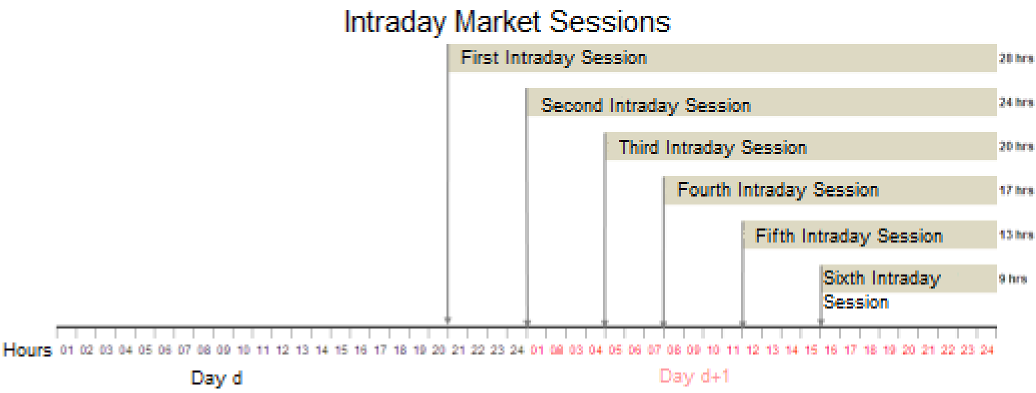

Figure 2.2: Illustration of the several Intraday Market sessions. Adapted from [12].

As Figure 2.2 illustrates, the several intraday market sessions cover distinct periods, with the timespan ranging from 28 hours for the first session to 9 hours in the case of the sixth session. All sessions close 3h15m before the starting hour of its schedule horizon. The last session available for trading covering from the 15th hour to the 24th, has its auction closing at 11h45, Portuguese time [11].

All market agents that took part on the day-ahead market sessions may join the intraday market auctions, as long as these are still running for the period in question. As they provide an ultimate stage for balancing contractual positions, even when bound by bilateral agreements. Intraday markets are thus an essential mechanism for providing trading parties a chance to revise initial planning on a closer term to the actual delivery time. This market is of special importance for renewable generators, like photovoltaic or wind energy producers, as they find it difficult to accurately estimate their power outcomes. The existence of a last resort platform for balancing results reduces a great deal of the risk associated with renewable generation, enabling the correction of first predictions of energy delivery and allowing for a more open approach to the wholesale market [11]. However, there are not many agents linked with generation from renewable sources operating in these terms.

The intraday market allows sellers to avoid the generally high costs of the balancing mechanism, consisting of penalty fines in case of energy deficits and gains below the marginal cost prices for the excess of production. This is a widespread strategy in Europe giving agents incentives to accurately predict their transactions, but also to raise the amount of power available in the intraday market. This supports the whole system's ability to balance generation and load, increasing its efficiency and reliability [13].

2.2.3 Derivatives Market - OMIP and OMIClear

The Portuguese division of the Iberian Market for electricity (OMIP) is in charge of the derivatives market sector, a power forward and futures market within the framework of MIBEL. OMIP has, since the start of its operations on 2006, experienced a steady development in terms of number of participants, transactions and interest in general [14]. Alongside it, there is its daughter company, OMIClear, owned entirely by OMEL and OMIP, which acts as a central counterparty, providing settlement for both power and financial trades. When a trade is in course, the OMIClear takes charge of the resulting positions, acting as a buyer for the producers and as a seller for the consumers, ensuring the security of the operation through various systems of risk control.

Operating on energy derivatives, this sector of the Iberian Electricity market handles the transaction of contracts based on an underlying energy asset, being in this case electrical energy, with a delivery date set in the future. This type of long term trading provides an effective risk management tool for market agents and, by increasing the amount of power and money circulating, enhances the market liquidity and helps creating reference prices. The main sort of energy derivatives traded currently in the OMIP include forward contracts, future contracts and swap contracts [12].

Forward contracts, as an "over the counter" form of transaction, are a customized bilateral contract, in which both parties agree to trade an amount of energy at a specified date in the future at predetermined price agreed on the date of the signing. These agreements arise from negotiation between two agents with no third party involved and are settled on a monthly basis and at the end of the contracted period by the clearing house. Buyers and sellers try to manage risk by settling on a reasonable price that minimizes possible losses upon the delivery date, when comparing to the price on the spot market (spot price). At the end of the deal, the seller has the obligation to deliver the amount of energy agreed and the purchaser is obliged to acquire it.

Future contracts, as forward contracts, represent a form of agreement for the trade of a commodity between a buyer and a seller with terms settled in advance. However unlike in the case of forward contracts, the price is made to be the remaining point of negotiation. In this type of trade, settlements are made daily through the clearing house, which acts as a centre counterparty, and refer to the differences between the negotiated price and the daily exchange price of electrical energy. OMIP has two types of future contracts, regarding physical delivery of electricity and the financial delivery of results. Both types of contracts share the same procedures during the trading phase, differing only in the allocation of the trading accounts. On the settling date, physical delivery contracts are sent to OMEL to be included in the day-ahead market as OMIClear ensures the financial balancing of both types of contracts [12].

Swap contracts are a type of agreement in which both parties agree on a specified price on the signing of the contract and then settle the difference between the arranged value and the spot price at the expiry time. There is no physical delivery in this kind of deal, as the goal is to manage risk. Contracts for the delivery of energy at a future date may also include other conditions such as the possibility to come through with the deal only if a certain price is verified (strike price) with these being called option contracts.

In the derivatives market, not only energy related agents are allowed to take part in the negotiations as other financial intermediaries are able to go into the trading activity. For example, at the start of 2010, 37 market agents took part in OMIP, where 30 were energy related entities and 7 corresponded to purely financial agents [15]. The main amount of the electrical energy traded by these participants was negotiated in compulsory call auctions. These are included in a parallel form activity of the derivatives market of MIBEL, which aims to complement the continuous market of OMIP. This can be achieved by imposing minimum percentages of energy transactions to participating agents[15], improving the liquidity of the market in general. These exchange-traded transactions are not exclusively independent from the “over the counter” operations, as some agents are active in one market while maintaining steady positions in the other. This flexible structure provides important mechanisms for managing the risk associated with power transactions. Market agents also benefit from the economic indicators generated by the activity and prices practiced on OMIP, which may aid in the development of a better strategy.

The existence of an efficient derivatives market is thus, essential to the development of the Iberian market for electricity, allowing agents to become more competitive, independently of their size, location or activity, ultimately promoting the liberalization of the market [13].

2.2.4 Characterization of the Iberian Power System

After having introduced the Iberian Market for electricity, from its composition to a detailed description of the functioning of its two separate divisions, it is now of special interest to this work to present a brief report on the Portuguese and Spanish Power systems. Having the Iberian Market as a background, it is important to have a clear view of the current generation capacities and energy production profile of both countries, as well as of the interconnection capability.

Generation Capacity

Two major production regimens are considered when looking at the generation capacities of Portugal and Spain; the Ordinary regime and the Special regime. The Ordinary regime comprises the main thermal stations using primary energy sources, such as coal, natural gas, diesel and others, as well as the large hydro units. The Special regime includes all the production from endogenous and renewable sources of energy, including wind, solar, mini-hydro, cogeneration, biomass and others.

Technology	**Portugal**		**Spain**	
	MW	**%**	**MW**	**%**
Ordinary regime	**10989**	**61,8**	**67977**	**62,9**
Hydro	5239	29,4	17766	16,4
Nuclear	-	-	7866	7,3
Coal	1756	9,9	11641	10,8
Fuel/Natural Gas	-	-	3498	3,2
Diesel	165	0,9	-	-
Natural Gas(CCGT)	3829	21,5	27206	25,2
Special Regime	**6801**	**38,2**	**40171**	**37,1**
Hydro	413	2,3	2058	1,9
Wind	4368	24,6	22900	21,2
Solar	282	1,6	6981	6,5
Thermal	1738	9,8	8232	7,6
TOTAL	**17790**	**100**	**108148**	**100**

Table 2.1: Overview of the generation capacities in Portugal and Spain at the end of 2013 [16][17].

According to the latest reports on the electric system from both countries, relative to 2013 and produced by the national transport companies and system operators, REN [16] and REE [17], it is noticeable a similar composition on both generation capacities. From Table 2.1, it is seen that the Ordinary regime accounts for over 60% of all the power production capacity, while the Special regime that includes solar and other renewable sources totals for 38.2 and 37.1% in Portugal and Spain, respectively. These high percentages of Special regimes production result from the mentioned support schemes practiced in both countries across the last decade.

The total installed capacity in Spain is around 6 times higher than that of the Portuguese system. Apart from the variance in size, there are other important differences in the generation mix in both countries, from which the most noteworthy is the presence of nuclear power plants in Spain, which contribute with 7.3% of the total installed capacity. Other significant aspects are the share of hydro power in Portugal that totals for almost 32% of all generation capacity in the country, between Ordinary and Special regimes, and the share of solar power in Spain, covering solar PV and thermoelectric units, which reaches 6.5% of the overall capacity.

Overall production of electricity

Technology	Portugal		Spain	
	GWh	%	GWh	%
Ordinary regime	**25758**	**52,4**	**168931**	**64,8**
Hydro	12146	24,7	34205	13,1
Nuclear	-	-	56378	21,6
Coal	10953	22,3	42384	16,2
Fuel/Natural Gas	-	-	6981	2,7
Natural Gas(CCGT)	1502	3,1	28983	11,1
Pumping Production	1157	2,4	-	-
Special Regime	**22079**	**44,9**	**111679**	**42,8**
Hydro	1337	2,7	7098	2,7
Wind	11751	23,9	54301	20,8
Solar	446	0,9	12951	5,0
Renewable Thermal	2692	5,5	5020	1,9
Non-renewable Thermal	5853	11,9	32309	12,4
Total Generation	**47837**	**97,3**	**280610**	**107,6**
Net Imports	2776	5,6	-6958	-2,7
Pumping Consumption	-1458	-3,0	-5769	-2,2
Gen. Consumption	-	-	-7012	-2,7
Demand	**49155**	**100**	**260871**	**100**

Table 2.2: Total electricity generation and demand in Portugal and Spain relative to 2013 [16][17].

Regarding Table 2.2, it is noticeable the high shares of renewable electricity, especially in Portugal, mainly due to the exceptional climatic conditions verified on the course of the year 2013. Hydro and wind power combined accounted for 51.3% of all the electricity produced during 2013. With solar (0.9%) and biomass (5.5%), the share of electrical energy based in renewable sources in Portugal totals in 57.7%, while in Spain that value is 43.5%.

It is also visible the different roles performed by Portugal and Spain in terms of market imports and exports. Portugal imports 5.6% of the total demanded electricity, while Spain exports through its interconnections with several countries almost 3% of the internal electrical energy demand.

Interconnection Capacity

Interconnection	Import (MW)		Export (MW)	
	Peak	Off-peak	Peak	Off-peak
Portugal	2400	2400	2400	2400
France	1300	1400	1000	1100
Morocco	600	600	900	900

Table 2.3: Interconnection capacity of the Spanish power system by the end of 2012 [18].

On Table 2.3 is shown the maximum interconnection capacity of the Spanish power system. Spain is connected with Portugal, with which it constitutes an Iberian Power System, but also with France and Morocco, linking the Peninsula with Europe and North of Africa and supporting its net exporter nature. As expected, the largest interconnection capacity is with Portugal, as the two electric systems of both countries are closely integrated.

2.3 Regulatory Framework

2.3.1 Independent regulation

The need for regulation in any economic sector is motivated by the existence of operating monopolistic utilities, which are still an important part of the electric sector in today's world, especially in transmission and distribution activities. Non-regulated activities from a dominant agent may lead to excessive prices, inefficient investments and operations and blocking of the entrance for competitors in the market. The liberalization of the electric sector evolves exactly in the opposite direction with the opening to new participants in the production and retailing activities. The regulatory and legal framework must act as a close interconnected driver to this movement, promoting the maintenance or even improvement of security of supply standards, which may suffer from the unbundling of the generation, transport and distribution activities previously operated by vertically integrated utilities.

In this new competitive environment, independent regulators promote the economic efficiency of agents and the system in general, by allowing new reliable competitors in the market, encouraging others to operate more efficiently in order not to lose their share of revenues. Also by setting the electrical energy prices, they help consumers to better decide on their purchasing choices, increasing the system's stability. Regulators also assess investments made by electric utilities, so that only necessary and worthy expenditures are implemented. This way, monopolistic revenues based on the amount of assets owned are limited and consumers are not overcharged with unnecessary costs. In addition, regulator entities provide incentives to increase the suitability of the system to every consumer by establishing specified levels of service and security of supply, while monitoring their effective application.

The existence of a regulatory body independent from any political or economic power is important to the development of an increasingly competitive and reliable electricity system. Also, regulating entities are key players to the conjoint operation and integration of separate electric systems [4].

2.3.2 Regulation at European level

The development of a single energy market for Europe, which started in 1996, involves the implementation of common rules for participating countries, in order to open and integrate the several electricity systems. However, power regulation in Europe is a highly complex matter as the regulatory models tend to vary from one country to another. Additionally, there is also instability in some regimes in what respects to energy policies due to the recent economic crisis, which is a serious setback considering long-term strategic planning. For instance, a lack of understanding of overseas regulation can induce utilities into making ill-advised investments, while the system operators at both ends of an international transmission link can be encouraged to make different decisions by the regulators [19].

Despite the inherent difficulties of incorporating different electric systems, Europe has been moving toward a liberalized and open system for power supply, supporting the development of cross-border activities. The European Commission has played an essential role in this evolution, by issuing several regulating documents and energy related Directives. The Directive 96/92/EC defined and structured the creation of the European electricity market. The 2009/72/EC, known as the Electricity Directive, establishes a set of shared guidelines regarding different matters such as power generation, transmission and balancing services, empowering regulatory entities to ensure the proper fulfilment of these commands [20].

Furthermore, new institutional frameworks have been set up to better support the continuous movement into a European Energy Market. The Agency for Cooperation of Energy Regulator (ACER) [21] was set up in 2010, with the goals of providing framework guidelines for national regulators in Europe, settling cross-border matters on which the agents involved cannot agree and monitoring and reporting to the European Parliament and Council.

Another institutional body created was the European Network of Transmission System Operators for Electricity and Gas (ENTSO) [22], in 2008. ENTSO was created to elaborate and implement network regulatory codes, ensure coordination of common network operation and publish annual reports on the development plans. It came as a successor of ETSO, the association of European system operators, created in 1999 to cope with the emergence of the Internal Energy Market across the European Union.

Despite an overall tendency to reinforce communication between national power regulators, a single European regulatory system is still a few years away, as major differences between some countries' electric systems will persist for some time. Nevertheless, there are some common trends to be noticed like the widespread downward pressure on the rates of return of companies, partly due to the debt crisis, and the interest in regulating for better efficiency and quality of service. However, as the European Commission is likely to promote greater convergence in regulatory regimes, costs may rise in some countries due to the needs of adaptation, which is a source of political controversy for national administrations. Government interference may be an obstacle in the development of a European internal energy market [20].

2.3.3 Regulation at local level

As part of the Iberian market for electricity, and as a member of the European Union, activities in the Portuguese electric sector are bound to converge with external regulation. In particular, Portuguese regulation for electric utilities is built upon the common grounds for national electricity markets, set by the Electricity Directive, mentioned above.

Regulation of the electric sector in Portugal is mainly at the responsibility of Entidade Reguladora dos Serviços Energéticos [12]. This independent body has the obligation of ensuring a fair and efficient operation of the entire sector. Namely, ERSE is in charge of ensuring the public service obligations inherent to all participants in the electric sector. The providence of a universal service, security of supply and the protection of consumers through regulated tariffs are some of the goals of this regulatory entity. Besides, ERSE must attest a proper integration with the electrical systems of the Autonomous Regions of Madeira and Azores. Also, as the share of renewables in generation keeps steadily increasing, the regulatory body must assure the feasibility of the introduction of these production sources, in a perspective of sustainability and environmental protection.

ERSE, as the regulator for market activities in Portugal, is responsible for assuring the transparency and equality in the access to competition to participants. Furthermore, as a member of the MIBEL Regulator's council, ERSE is responsible for developing the regulatory structure needed to the incorporation of the Portuguese electric system in MIBEL and in the European electricity value chain, as the liberalization of the sector moves forward.

There are other institutions providing regulatory services for the sector [23]. DGEG – Direcção Geral de Energia e Geologia [24] is a part of the Portuguese Public Administration, and provides assistance in the creation, promotion and evaluation of energy related policies, in a perspective of sustainable development and efficient use of energy resources in a broad-spectrum. Autoridade da Concorrência (AdC) also offers regulatory assistance to competitive sectors, such as the retailing activities, by proposing laws and rules to competent institutions and through the identification and investigation of practices prejudicial to free competition [25].

The regulation of the Portuguese electric system, from the joint operation of the entities mentioned above, is aimed at guarantying the efficiency, transparency and competitiveness of the sector, through constant monitoring and supervision, in a scope of integration in the European electricity market.

2.4 Virtual Power Plants

2.4.1 Concept

The introduction of Distributed Energy Resources (DER), with production, storage or demand capacities, is increasing at a fast pace all over the globe, mainly due to the requirements of a sustainable energy system with lower environmental pollution and improved efficiency. Meanwhile, it has been in course a progressive liberalization of the electricity sector, evolving from a paradigm where vertically integrated utilities were the norm to a gradually more competitive and decentralized structure. In this context, a growing number of distributed generators have been set available. However they have been installed with a focus on the connection side rather than on the total system integration, which raises some relevant questions [3].

First of all, since this form of generation includes mostly renewable production of intermittent and with power outcomes difficult to predict, such as wind energy or photovoltaic systems, otherwise classified as non-dispatchable, their access to the market is limited. These units are subject to penalty fines related to unbalances in production, which, due to the nature of said generators, may be frequent and cause them to become economically unviable. Additionally, as many DER are working individually, as they are usually geographically separated with different ownerships, their entrance in the market is even more difficult. The small amount of power produced and the inability to adapt their outcome to the load, confine them to the satisfaction of local needs, not being able to assist the entire grid. This explains why one of the main mechanisms to support the development of renewable technologies has been given through feed-in-tariffs schemes, which guarantee a fixed fee for the operation.

If the activity of these distributed energy resources was to be aggregated, the whole sector would be enriched from it. This can be achieved by using the Virtual Power Plant (VPP) concept, which is based on the idea of combining the capacity of a portfolio of many DER, in order to create a single operating profile. In this approach, individual DER would be able to gain access and visibility across energy markets, benefiting from better opportunities and greater chances of economic success. Also, the uncertainty factor related with the nature of renewable generation could be reduced, as the aggregator agent would be able to blend several different agents, optimizing their production profiles to better adapt to the loads. The electric system would benefit as a whole from the optimal use of the available capacity and increased efficiency of operation [26].

On matters of long-term sustainability, environmental concerns could be diminished with the gradual replacement of polluting production units with renewable generation. Several individually implanted generation methods, from privately owned photovoltaic systems to mini-hydro power plants, could be fused together in a complementary way through a VPP and participate in the market with similar functionality as conventional generating units. By overcoming reliability and controllability issues, power production from renewable sources could become an even more important factor in facing worldwide environmental issues.

Several variations of virtual power plants can occur, deriving from the different set of renewable and non-renewable generators and storage devices they can integrate. Also, the geographic location of the elements composing these aggregator agents can influence their role in the electric system. Some VPPs can play an exclusively commercial role (CVPP), assembling the power outcome of several local units and introducing them in the market as a single entity. Meanwhile others may perform a more technical operation (TVPP), being able to adjust the production profile of their generating components or even provide ancillary services to the system, such as energy storage or frequency regulation. The characteristics of the distributed energy resources involved and the degree of incorporation in the VPP determine the operation of these agents [3].

2.4.2 Smart Grids

Virtual Power Plants are thought to play an important part in what the European Commission predicts to be Europe's electricity system of the future [27]. General consumers' increasing proactivity and awareness to energetic issues, the proliferation in electric vehicles and smart appliances and the growth in DER give rise to a need for a new and more intelligent electric system that is able to accommodate all these new variables.

According to [28], a Smart Grid is "an electricity network that intelligently integrates the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies". This can be made possible through the present availability of innovative technological solutions such as smart meters, two-way communication systems and intelligent autonomous controllers. The ability to connect all the agents of the electric system with real-time information makes possible, not only for producers to improve the operation of generators from different technologies, but also for consumers to take an active role in the system's optimization, by controlling the usage of their electric utilities.

An electric grid with access to live information and control on both load and demand sides is able to deliver enhanced levels of reliability and security of supply. The chance to add or remove generation units to the production side, due to failure in other units or changes in demand, or the possibility to shut down home electric appliances when needed, greatly increases the flexibility of the electric system.

As part of the European strategy to the integration of low carbon generation technologies, Smart Grids provide the capacity to better adapt to sudden fluctuations in solar PV or wind power output, contributing to the further proliferation of these DER. The introduction of more active transmission and distribution networks in the form of Smart Grids is crucial to the development of the Internal Market for Energy, which highlights improved efficiency and lower CO_2 emissions.

Smart Grids are also believed to help in the reduction of energy consumption, lowering polluting emissions and enabling financial savings. Due to the current economic situation in Europe, most modern consumers are interested in following their actual electricity usage. With home installed smart meters, these consumers are able to monitor their real-time consumption and are encouraged to save energy. The EC estimates that in a Smart Grid environment, the annual household energy consumption can be lowered by 10% with CO_2 emissions dropping by 9% [27].

Smart Grids are expected to bring great benefits to all the agents of the new electric system, from grid operators that can manage the network more efficiently and retailers that can offer an improved customer service to the improved role taken by the consumers that are now able to actively take part in the supply chain. Furthermore, since Smart Grids promote the coexistence of conventional and renewable power generation, they create conditions for the entrance of new players in the market, with innovative solutions, while allowing the general reliability of the system to be kept or even improved. The new electricity network contributes ultimately to the further liberalization of the market for electricity and to the technological and economic development.

Thus, the implementation of VPP corresponds to the full implementation of the Smart grid concept.

2.4.3 Related work

In this section, a selection of previous studies on VPPs and Smart Grids, which were thought relevant to the development of this project, will be presented. For each case, a brief description of the work done, as well as some important conclusions and contributions are going to be shown.

2.4.3.A RWE Virtual Power Plant in Germany

This study reports a functioning VPP structure in Germany [29], [30] and [31]. RWE, an important energy company, partnering with Siemens, implemented a VPP project that sought to integrate combined heat and power (CHP) plants, wind and biomass. The combined generation capacity was to participate on the European Energy Exchange market, in operations of power purchasing and providence of ancillary services to the grid.

RWE Energy's trading department assumed the aggregating functions, while Siemens provided the IT knowledge and technology with innovative solutions. One of these features is the Distributed Energy Management System (DEMS), which, combined with generation site controllers, centrally monitors and controls production at each unit, with demand-side information, such as electricity prices and load requirements.

At a primary stage (2008), nine hydroelectric units in Sauerland, North Rhine-Westphalia, with an overall production capacity of 8.6 MW, constituted the initial VPP. It is projected that in 2015, with the introduction of further dispersed power plants across Germany, the total capacity should account for 200 MW.

It was stated that the communication system is crucial for the operation of a VPP, as power exchange markets require almost real-time information on production estimates in order to enter. Also, a minimum capacity of 500 kW was reported to be the threshold for successful economic activity of similar structures, due to significant initial investment costs. Another important aspect for the operation was the relationship with customers, which needs to be transparent and trustful.

2.4.3.B The Danish Island of Bornholm

The report in [32] refers to another example of a working VPP. In this case, around 2000 households in Bornholm, Denmark are connected to the grid in a way that enables the reduction of power usage during peak loads, with the trade of unused capacity at market prices. With a high share of wind power in the Island, this system proves to be of major significance.

In response to peaks in electricity prices and according to previously set conditions, households equipped with gateway controllers automatically turn off their appliances or adjust the thermostat. The unused power capacity is then aggregated and sold to consumers in need, allowing for reductions of around 20% in peak loads. The alternative to meet this demand would be to increase production, which would have significant economic and environmental costs.

Much like in the first work reviewed, it is indicated the importance of the communication system between central management and local control of production, as many DERs equipment appear not to have been designed to interact with modern information technology (IT). It is also suggested that, when a capable communication infrastructure is set, a lot more can be done in terms of operational control and even in shaping the energetic behaviour of the customers.

2.4.3.C VPPs as cooperatives of DERs

In the study present in [33], to tackle with the fact that individual DERs are often excluded from the market, the authors propose that these are combined to form cooperatives of agents that may be profitably included in the electric grid.

An interesting pricing mechanism is tested as an alternative to the commonly used feed-in tariffs. Remuneration is influenced by the accuracy of production estimates from the generators but it also contains a factor that increases with the amount of energy traded. Individual producers are thus encouraged to provide precise generation predictions, promoting the reliability of the system, and cooperatives are led to gather as many DERs as possible. Internally, cooperatives' members are evaluated on the contribution to total revenues and so, consistently unreliable producers are identified and penalized.

The proposed system is verified in an experimental wind farm in Spain, and the results provide some coverage over the initial claims. DERs almost always benefit from being integrated in cooperatives, rather than taking part in the market individually. The pricing mechanism promotes transparency in the interaction between cooperatives and the grid, and also between the individual producers and the cooperative, as accuracy in estimations is encouraged. Ultimately, the proposed methods seem to promote security of supply and production efficiency.

2.4.3.D Operation of a VPP in the market

In the paper presented in [34], it is proposed a model of a market based VPP, as a mechanism for allowing individual DER units to take part in the electricity markets. According to what is described, every small producer has access to market activities, but only to sell generation that exceeds their individual consumption, a common feature to the model to be implemented in this project.

Two different scenarios of market operation are presented. The first is a general bidding scenario, in which DER units submit generation bids through the VPP, according to price forecasts for the market session in question. There is also a price signal control scenario, where the VPP operator sends a series of price signals to which the individual producers respond on their availability to sell, until a final value is reached.

Both operational systems are tested in a simulated environment containing 4 households equipped with identical CHP units running on gas, each with different daily load profiles of electricity. An estimation of the day-ahead market price is provided, as well as the price at which households are provided with gas and power. A flawless communication system is assumed.

As a result, both market scenarios produce similar outcomes regarding the operation of the VPP. Householders only seem willing to bid their exceeding power when the market price is at a peak that equals the price of the electricity bought from the utility and is well above the price of the gas needed to run the CHP unit.

2.4.3.E Bidding strategy of a VPP

The study described in [35] and [36] addresses the participation of a VPP in a joint market of energy and ancillary services. A non-equilibrium model is proposed to design the bidding strategy, considering several types of constraints, such as individual DER restrictions, the supply-demand balance issue and distribution network limitations.

In this paper, the VPP is composed by distributed generators, units capable of power storage and end consumers with controllable loads. A form of centralized control is assumed where the VPP handles all market operations, being responsible for all technical and economical functions across the structure, with the aim of maximizing profit.

With estimations of loads and market prices based on historical data, retail rates for end consumers and cost functions of production and storage, the VPP is able to place its bids in both markets. This mode of operation is similar to the one to be implemented in the model of this project. Given all constraints and initial conditions, an optimization problem is formulated and the solution, based on a genetic algorithm, is tested in different scenarios, regarding participation in one or both markets and several levels of market prices.

It was verified that, in order to be profitable, the VPP must act in the energy market both as a producer and consumer. When the market price for energy is above production costs or above retail rate, power is sold to the market, by direct generation or load reduction, respectively. When market prices are low, the VPP can buy energy and sell to end consumers at a higher value. As for activity in the reserve capacity market, the authors found that it was independent of the role taken in the energy market.

2.4.3.F Multi-agent control systems for VPP

Unlike the centralized operation of VPPs linked to most of the previously reviewed works, this study, [37], proposes a form of distributed control, based on a multi-agent system (MAS). This system is thought to improve overall operation of a VPP, by optimizing the individual performance of each DER.

A multi-level control structure is designed, where each production unit or controllable load is represented by an agent. According to physical constraints, such as proximity and network limitations, these agents are grouped in MAS, communicating between each other and with other similar MAS. Groups of several MAS join to form larger MAS, in order to participate in the market. The model was tested in an experimental site containing 170 households, one diesel generator and several PV units.

It was found that by assuming each agent's operation as an optimization problem, rather than optimizing the system as a whole, it is possible to include more detailed information, such as individual cost functions or operating conditions. However, since there is more information to process and thus, more restraints to respect, the solution obtained for the system's operation could be too simple to avoid delays in the communication processes. As for the relationship with homeowners, it is stated that a form of local control is preferable to having someone from an external point taking final decisions on power production or load control matters.

2.4.3.G Viability analysis of Virtual Power Plants

In this work [38], a study of economic and financial feasibility was performed on the possibility of a company operating as an intermediary between a set of privately owned photovoltaic systems and the market. This project has as background the MIBEL daily market, but focused on the Portuguese distribution and retail framework.

A market simulator and a financial analysis model were built and run with some starting assumptions. It was considered that each client had one solar PV panel and could only sell electricity that exceeded its private consumption. Also, all electricity taken to the market by the virtual company was sold as the VPP agent acted as a price taker with no power to influence the results. Historical data on household consumptions, power production and daily market prices were used to model the individual loads, solar PV output and average expected selling price for the available energy.

The simulation runs for 8 years with a starting value of 4200 clients and a 4% growth rate per year. It was found that, in these initial conditions and with a well-defined cost structure linked with the functioning of the company, the operation would achieve positive cumulated cash flows on the course of the 6th year. It was stated that a minimum of around 3800 clients would be necessary for the financial validity of the project.

2.4.4 Considerations to be taken into account

After analysing this set of studies on the field of VPP and Smart Grids, several important aspects were retained for future work in the area:

- Vital importance of the communication systems;

The exchange of information between production units, controllable loads and VPP administration is crucial for the whole operation.

- Relationship with householders or owner of generation sites;

Contact with customers must be clear and transparent for the project to run correctly, from production schedules to permission to shut down home appliances.

- Market price is important for the project's success;

Individual production units benefit most of the time by being integrated in a VPP, but that is highly dependable on the price at which they sell energy. Production and investment costs and feed-in-tariffs are obstacles to success in market activity.

- Centralized or distributed control of VPP;

Depending on the situation, a different form of VPP control can be advised.

- Threshold in the generation capacity for economic feasibility;

There is always a minimum amount of available power for the VPP project to be financially successful, depending on the general conditions of each project.

3 Literature Review

3.1 Modelling Electricity Markets - Purpose and Benefits

The special characteristics of electricity as a commodity make electricity markets one of the most distinct markets operated at the present time. The continuous need to balance supply and demand, the unfeasibility to store large amounts of electrical energy and the physical limitations in transmission and distribution are constant challenges in a sector that is moving towards liberalization and decentralization. More and more firms are competing in generation and distribution activities and electric systems are becoming bigger and more complex, with the coexistence of different production technologies and the need for these to be efficiently integrated. Participants in the electric system, from producers to regulators, are exposed to increasingly higher risks and it is greatly beneficial for them to have an accurate representation of the market structure and activity as a support during decision processes. Market simulation tools are the most commonly used solution to assist in this aspect.

Depending on the interested party, market modelling can have many purposes. In the case of consumers and small producers, simulation tools can aid in the making of better decisions regarding the trade of electricity via spot market or bilateral contracts, by means of precise price forecasting.

As for large generating firms, market simulation may provide insights on the correct bidding strategies in spot markets or on the balance between participation in energy trading or providence of ancillary services. Also, owners of different generation technologies can improve their coordination of power sources in more complete tools that incorporate production cost functions and weather forecasting. Furthermore, through long-term simulation programs, it is possible to analyse the opportunity for future investments in new generation capacity.

System operators also benefit from proper market simulation, by analysing network constraints and thus avoiding system failures. Moreover, as the system grows, operators can evaluate the need for improvements in network capacity and plan the correct integration of significant amounts of intermittent renewable energy in the grid.

For regulatory bodies, simulation tools can help to predict the outcome of new market rules, providing an opportunity for testing measures to promote competition and system reliability. Similarly, by analysing market structure and participants, policy makers can study the influence of renewable energy in the price of electricity or the effect of large shares in market dynamics.

Modern simulation tools provide all agents in the electric sector with the opportunity to test their decisions in a virtual environment, by incorporating many features of real power systems, such as current network capacity, demand side information, individual power plant data and an updated legal framework. Despite including similar content, electricity market simulators may be structured differently, according to the purpose they are built for.

3.2 Diversity in market modelling

Different agents taking part in the electric system may want to perform distinct analysis before engaging in decision processes. A generating company would prefer to find out the best strategy to maximize its profit in market participation, while the system operator of said market would be interested in testing the best way to integrate the action of all agents, buyers and sellers. To cope with this diversity of interests, different market simulation tools have been created throughout the existence of the electric system, particularly during the last decades, which have brought the liberalization movement and significant technological advances.

According to [39], which presents a review of the most relevant modelling tools to date, the large diversity of market simulators can be organized in three major groups: optimization models, equilibrium models and simulation models.

Optimization models are often used by generating utilities as an instrument to test strategies of profit maximization. In these simulators, the market environment is created as a function of the price clearing process, giving rise to two sub-groups in this type of models. In *Exogenous Price* models, a context of perfect competition is represented, as the company has no influence in the final price of electrical energy. Market price is taken and the firm's profit depends only on the amount of power that it is able to sell. In *Demand-price Function* models, both the demand curve from consumers and supply curve from all other competitors are taken into account and so, the market price can be influenced by the firm's generation. Independently of the price clearing process considered, optimization models are mostly intended to assess a single entity's market activity.

Equilibrium models are based on the notion of balance between supply and demand and intend to simulate market activity considering competition among all agents. They are grounded on a mathematical definition of equilibrium and are usually more suitable for analysis from an economical point of view. There are two main sorts of equilibrium models but the most widely used is based on *Cournot Equilibrium*, which is a known economic model used to describe markets of imperfect competition. In this approach, generating firms compete to supply the optimal amount of energy in response to the opponents' strategies. The other major group of equilibrium models is based on *Supply Function Equilibrium*, in which generating companies compete by presenting their optimal supply curves. This is a more complete approach, as the companies' bidding strategies are presented as quantities in function of the market price. However, due to its more intricate mathematical structure, as a set of differential equations is required to be solved, instead of *Cournot*'s algebraic functions, it is harder to apply and thus, it has fallen behind in terms of number of users.

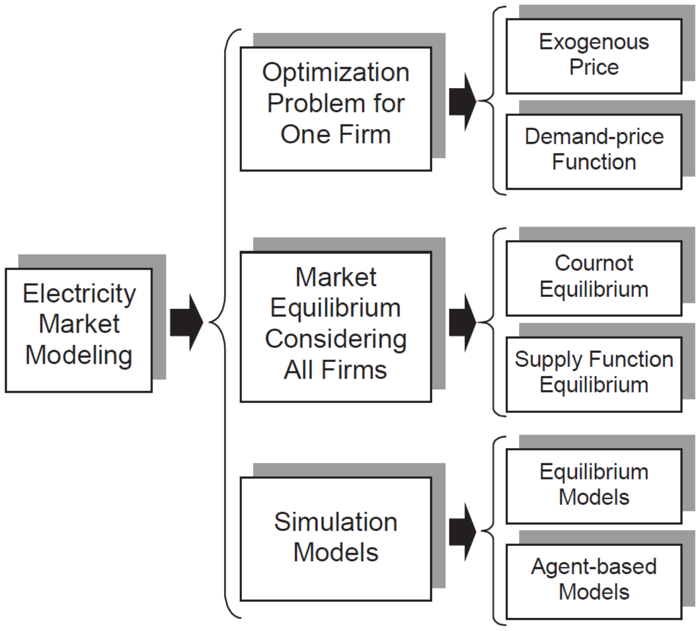

Figure 3.1: Electricity market modelling trends [39]

Simulation models, the third group of major electricity market representations as seen in Figure 3.1, are an alternative to market equilibrium models, as both have in common the purpose to emulate the activity of all participants. Nonetheless, instead of relying on a formal definition of equilibrium that may be too complex to produce viable solutions, simulation models are based on sets of sequential instructions linked with important features of generating firms, such as production schedules or the creation of supply curves. Two sub-groups exist among simulation models. The first, a class of *Equilibrium Models*, is closely related to the major group already mentioned, as *Cournot* and *Supply Function* equilibrium are also considered. Yet, rather than formulating and solving a mathematical problem, solutions for the system's optimization come from iterative processes, where, based on relevant information, each firm adapts its bidding strategy from the previous step until equilibrium is reached. The second group of simulation models consists of the *Agent-based* models. This approach relies on the premise that participants in the market, represented as agents, learn from past experience. Based on historical sets of information from market activity, each agent adapts its strategy in order to improve its results. In most examples, agents base their new bid in past information of market prices, demand or production data, in order to maximize their profits. Simulation models and particularly *Agent-based* models are very flexible in representing complex systems like an electricity market, because of the dynamical character of the *agents*, which are autonomous, reactive and social interactive. For these reasons, this approach has been increasingly used in the construction of market simulation tools [40].

3.3 Related work

In this section, it is presented a description on a particular selection of market simulation tools that were considered relevant, developed to meet the needs of different agents in the electric system. Some of the reviewed simulators are professionally developed while others are the product of academic investigation.

3.3.1 WASP (Wien Automatic System Planning Package)

This tool was initially created by the Tennessee Valley Authority and Oak Ridge National Laboratory of the United States of America in 1972 [41] to meet the needs of electricity planners. It is one of the oldest and most widely used electricity market simulators and it is recognized as a standard approach for long term capacity planning by the World Bank. Maintained by the International Atomic Energy Agency (IAEA) [42], it has the purpose of assisting regulators and system operators in planning the expansion of the electric system. Three newer versions have been launched since the first and these are freely made available for member states of the IAEA, and are used in over 100 countries.

The WASP allows for its users to obtain the most economically efficient expansion plan for a power generation entity over a period of 30 years. Given a set of up to 12 distinct load duration curves to represent the demand side during the simulation runtime, the simulator estimates the future cost function (capital investment, fuel, operation and maintenance, cost of unserved energy, etc.) of each possible power unit to be added. A variety of generators are evaluated, from fossil-fuel, nuclear, biomass to hydro power plants, and, through iterative comparison processes, the best sequence of capacity additions is obtained, based on minimum total costs. The solution is bound to obey to a set of constraints, which include maintaining the system's reliability, respecting environmental legislation or abiding by the availability of certain fuels.

The simulator has a modular structure, where each module is responsible for part of the intermediate calculations. In this way, input data such as demand forecasts, or future estimations of fuel availability and prices can be computed separately, with the results being made available for the user, who is able to monitor the evolution of the simulation. This is an important feature that is going to be implemented on the development of this project.

Previous application of the WASP include studies on biomass power generation, dependence on imported fuels and the role of nuclear power in electric systems [43].

3.3.2 AURORAxmp

The AURORAxmp Electric Market Model was developed by EPIS, Inc. [44] and was introduced in 1997 to simulate competitive wholesale electric markets. It is one of the most complete software pieces available, as it is used by most players in the electric system, being capable of performing short and long-term price forecasting, resource valuation, risk analysis and capacity expansion planning. The most recent version, dated from 2014, contains an extensive database, including complete representations of most electric systems in North America and Europe, from generation units, transmission networks to emission rates and fuel prices.

This simulator uses hourly unit commitment and dispatch logic mechanisms to perform market price estimations, from day-ahead markets to long-term studies, divided by geographical areas and trading zones. As for network modelling applications, this tool resorts to its security constrained optimal power flow information and grid maintenance schedule management to compute locational or system marginal prices, allowing for a proper representation of the distribution system on market results.

Regarding generation expansion planning and unit retirement, through genetic algorithms and linear programming, the AURORAxmp determines the optimal selection of future production assets for periods of over 20 years. For this task, it combines sets of different generation units with complete description of their features, including wind and hydro, with levelised net present value (NPV) of market outcomes. The representation of generation units includes start-up costs, ramp up times, lifecycle information, fuel availability and costs and also wind and hydro shaping tools [45]. In term of risk and uncertainty analysis, this simulator uses Monte Carlo methods to evaluate the effects of fuel, load and hydro fluctuations and also price and volume variance on market activities.

As a professionally developed tool, the AURORAxmp is used by generation units, market operators, government agencies and regulators, investors and energy consultants, and previous applications include modelling CO_2 emission reductions in the Northwest power system in the USA and a strategic portfolio analysis by a Canadian power company [44].

3.3.3 WILMAR Planning Tool

The WILMAR (Wind Power Integration in Liberalized Electricity Markets) planning tool was created as a research project from a consortium supported by the European Commission. Its first version dates from 2006 and it has a primary goal of modelling the introduction of renewable power technologies into large liberalized electric systems, such as the Nord Pool and the European Power Exchange. It is now commercially available and it is suited for regulators, operators and producers as it is able to compute integration costs and optimal dispatch of wind power units into the grid [46].

The WILMAR tool, as other simulators described here, has a modular structure composed by a number of sub-tools and databases, all of which are joined together in a Scenario Creation Tool and a Scheduling Model. The Scenario Creation Tool takes as inputs wind speed and wind power production time series, electricity demand data and load forecast accuracies for different time horizons, and it generates wind power production estimates, load forecasts and the demand for positive reserve motivated by the total forecast error of the system. This is an important feature that should be taken into account in the development of the project. The Scheduling Model then takes this information and, through an optimization process, obtains the minimal expected value of the total system's operational costs, considering fuel, emission and other variable costs, start-up costs and taxes [47].

This tool is mainly used to simulate large electric systems over a period of 1 year with hourly steps. The calculation of replacement reserve demand, from 5 minutes to 36 hours' time horizons, enables

WILMAR to specify the effect both on system stability and costs of high levels of wind power in electric systems. This simulator contemplates all thermal generation and other renewable technologies, with exception to solar and geothermal and electricity storage in the form of pumped hydroelectric, battery and compressed-air energy.

Apart from analysing fluctuations in total system costs due to increased wind power penetration, the WILMAR has also been used in other projects and studies including the evaluation on how electric boilers and heat pumps improve wind power integration or the modelling of the introduction of wind power on the island of Ireland and onto the Nordic energy system [43].

3.3.4 RETScreen

The RETScreen Clean Energy Project Analysis Software is a free decision aiding tool created in 1996 by the Government of Canada, in collaboration with industry and academic institutions, to assist energy planners in addressing the reduction of pollution by means of integration of clean energy sources. It is not a market simulator in its essence, but instead a tool that models the introduction of renewable generation in the grid, with its advantages and disadvantages. This software is currently used in over 200 countries and territories [48] and it is greatly useful for regulators, generators and governmental institutions to assess energy production, financial feasibility and risk and environmental advantages of numerous types of renewable energy projects and energy efficiency solutions.

On the basis of this tool is a comparative nature that evaluates the proposed renewable project against a base scenario composed by the existing conventional technology or measure. To achieve this, the RETScreen software is provided with data relative to all thermal generation and renewable resources, as well as heating and cooling and energetic efficiency projects. The tool is also equipped with product and project databases from pre-existing solutions and it has access to hydrology and climate information, obtained from worldwide ground stations and NASA satellite data.

The RETScreen uses a five step integrated analysis, enabled by its modular structure, that covers energy issues, cost evaluation, polluting emission analysis, financial assessment and sensitivity/risk analysis. On the energy module, the user indicates location, type of technology and loads and receives as output a value for the annual generation. On the cost analysis, with inputs relative to variable and fixed costs, the tool produces a report for the annual projected costs. The emission analysis provides information on the amount of pollution avoided with the proposed solution. The financial module provides insights on a variety of indicators and evaluates project viability, with user specified values for inflation, taxes and other parameters. The risk module, which is not mandatory, performs analysis on constraints that may affect the viability of the project, for example the price of electricity or the value of emission credits.

The described tool has been involved in several projects, including the installation of a Wind Farm in Ireland, the integration of solar PV production on a school building in Canada, or the feasibility analysis of a large solar PV project in Egipt [49].

3.3.5 EMCAS

The Electricity Market Complex Adaptive System (EMCAS) model was developed in the USA in 2002 by the Argonne's Center for Energy, Environmental and Economic Systems Analysis. It was created to tackle with the dynamical nature of electricity markets, in which the needs of competing players differ from one to another and even alter during the course of time [50]. Participants in the electricity markets are represented as agents in this model, each with its own set of goals, decision-making rules and acting patterns. The EMCAS is able to model the activity of generators, regulators and system operators.

At the centre of this tool there is an agent-based model in which participants are represented as independent entities with personalized features making decisions according to a set of available information, such as historical data on prices or loads. By means of complex adaptive systems, the agents are able to learn from their past experiences and adapt their future action plans to best suit their individual objectives [51]. The EMCAS is capable of simulating all costs, from a database including thermal and renewable generation as well as storage and conversion technologies and also analysis investments in generation expansion.

This simulator has a modular structure containing several interaction layers that create the environment in which the agents cooperate. A physical layer contains the transmission and distributed framework and respective limitations. Several commercial layers cover the operating companies, bilateral contracts and pool markets. Finally there is a regulatory layer that includes the operating rules that can range from a monopoly situation to a fully deregulated market. An EMCAS simulation, running over the described levelised structure, covers six time-frame decision levels, from hourly dispatch to long-term planning, in which agents determine relevant information, such as power consumption and prices, and decide on the actions to take to meet their goals.

The EMCAS has mainly been used on studies of restructuring of electrical systems in Europe, Asia and the United States. Some of these applications include analysis and expansion planning of the Iberian markets, study on market competitiveness of the US Midwest power market and price forecasting and unit commitment in UK electricity markets [43].

3.3.6 MASCEM

The Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) was firstly created in 2003 by a group of investigators [52] and it has since been developed by the Knowledge Engineering and Decision Support Research Center (GECAD) in the Instituto Superior de Engenharia do Porto (ISEP). This academically developed agent-based model is meant to provide a decision support tool for most of the entities in the electricity market, including generators, consumers, market operators, system operators and, more importantly, VPP entities (producers and aggregators).

The MASCEM is able to simulate day-ahead, forward and balancing markets and also bilateral contracting and providence of ancillary services. By means of reinforcement learning algorithms and Bayes theorem, buyers and sellers are able to analyse previous results as well as market and competitor related data and weather forecasts, and adapt their own strategies (time-dependent or behaviour-dependent strategies) to improve their future outcomes [53].

In this simulator, VPP agents in the form of commercial aggregators are modelled as independent multi-agent that are viewed from the market perspective as selling entities. A relevant feature from the MASCEM that may be included in the development of this work is the set of different market strategies available to VPP agents, namely the balancing between production and generation forecasts of non-dispatchable energy sources and the assurance of reserve power to accommodate fluctuations on the contracted output [54].

On the background of this simulator lies a modular design of an electricity market at three levels, each with its own operator, negotiation methods and clearing processes. This stratification is made according to geographical information and characteristics of the agents, and range from continental markets, national and transnational markets to local and smart grid markets.

As a product of academic investigation, the MASCEM has been applied in studies on the coordination and remuneration of distributed generators included in VPP [54] and in market simulation and integration [55].

3.4 Conclusions

Once analysed this set of simulation tools, it came as a confirmation that the modelling of electricity markets is an activity with over 40 years of history. It began with government supported simulators aimed to provide support for planning line expansion and evolved over the time with the development of the electric systems into large and diversified tools that can be adapted to the needs of every agent.

After studying this group of simulators, a few important features must be recalled and taken into consideration for the development of the simulator in the current project.

- Modular structure

A common aspect to all analysed models that increases practicality and building simplicity and enables the separation of different contents for intermediate results;

- Historical data

Again, most analysed models resort to historical sets of information on market prices or electricity consumptions to estimate future behaviours on those quantities;

- Weather forecasts

On models representing generators based on renewable sources of energy, weather forecasts are a crucial aspect to the prediction of power output and, therefore, the proper participation in electricity markets;

- Well defined regulatory and market framework

Essential aspect, present in all investigate simulators, whether they are modelling day-ahead markets or planning long term expansion. It is important to correctly adapt the functioning guidelines of our model to the commercial framework that it is supposed to represent.

4 Specification of the model

4.1 Brief description

Despite the study and analysis on the set of different simulating tools presented in the previous chapter, it was decided in this project to create a new model. This decision was based on two different aspects. First, it was better in the learning aspect to develop all the sub-modules and interconnections that integrate a modelling tool, as it would provide a more complete and profound understanding on the structure and functionality of an electricity market simulator. Second, regardless of the similarity of some of the models revised in terms of objectives and background, they were not openly available for access and configuration to this project's needs. Given this, it was chosen to develop a new modelling tool with its major features emulated from those used by the set of simulators analysed.

As other electricity market simulators described in the previous chapter, the model implemented in this project intends to represent the action of market players in order to study their best strategies to a successful operation. More specifically, this simulator has the aim to represent the role of a VPP agent acting as an intermediary between a set of domestic producers and the market for electricity.

This model, constructed through MATLAB software [56], has the MIBEL day-ahead market as background, focusing on the Portuguese regulatory and commercial framework for operational purposes. In this setting, our VPP agent will aggregate the electricity generation of a number of clients owning solar PV installations and will then take it as a whole to the market.

An important feature in this work is that the aggregated value of electricity taken to the market is composed by the amount of power produced that exceeds individual consumption. Each client will only sell if it presents a positive balance between generation and consumption at a specific time period. The total available energy is then sold at a given price and the revenues made are analysed upon a set of important parameters.

The market scheme defined in this project depicts an approximation to a new regime of small production proposed by the Portuguese government [57] in which, individuals are able to generate electricity for private consumption and sell the exceeding amount to the market sell the exceeding amount to the market at a price which is 90% of the average price of the market price in the previous month. It will also be interesting to assess the impact of this new system compared to the current legislation for the sale of privately owned electricity generation. A more detailed description of the simulator is presented on the following sections.

It should be noted that throughout this project, the terms energy and power are widely used and applied to describe similar quantities. Since electricity markets are based on the delivery of electrical energy for periods corresponding to one hour, the calculations of energy values will correspond to an average value of the power made available during said hour, which in turn are based on average values of temperature and solar irradiance for the same periods.

4.2 Structure and operation

Following the trend of most simulators, the one in development in this project will also have a modular structure. This feature, is mainly characterized by an isolated construction of each of the distinct parts of the model, enables a more accurate operation prior and during actual simulation work. Programming errors are more easily identified and corrected and there is a possibility of generating intermediary results, which enhances the model's functionality.

This simulation model contains three major input modules, referring to the production of electricity, consumption of electricity by the individual owners and market data. Information resulting from the operation of these modules is then used in the operational simulator in order to obtain the expected results.

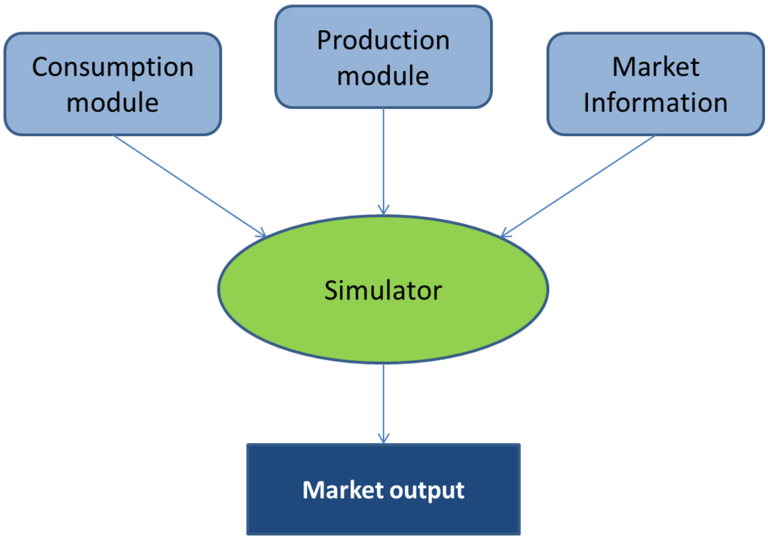

Figure 4.1: Illustration of the structure of the presented model.

Production module - An algorithm takes as input weather forecasts and executes predictions for the output of power for a specific time period.

Consumption module – Here are made estimations of consumption of electricity for each time period based on historical data.

Market information – In this part, the available amount of energy is calculated from the set of producers and market prices are obtained for market participation.

Simulator – Results are computed based on the input modules with an iterative operational process.

4.2.1 Production

The production module is based on sets of weather forecasts provided by the Grupo da Previsão Numérica do Tempo – Instituto Superior Técnico [58]. This information contains hourly predictions for the following 7 days of, among other data, temperature and solar irradiance at ground level. This solar irradiance consists of **shortwave downward radiation**, an estimate of the total radiation, both direct and diffuse, that reaches the Earth's surface. There will be no additional deliberations made regarding the incidence angle of the solar irradiance or its effects on the output power, as it is considered that the solar panels are placed on a surface parallel to the ground.

In order to obtain an amount of electricity output based on the given weather conditions, it was used a mathematic model of conversion of solar irradiance into electrical energy through solar panels, the **Three Parameter Model**, presented on [2].

The Three Parameter Model

This mathematical model implies that a photovoltaic cell can be represented by an equivalent electrical circuit, presented on figure 4.2. I_S represents the electric current generated by the photoelectric effect occurred on the cell surface upon being hit with a radiation beam. I_D is the current that crosses the diode that symbolizes the cell's p-n junction. V and I represent the voltage and current at the cell's terminals, respectively.

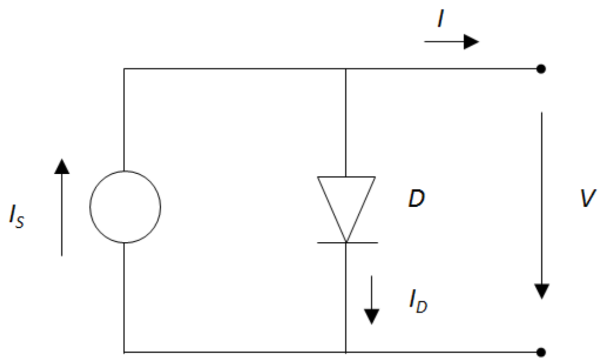

Figure 4.2: Equivalent circuit of a photovoltaic cell in the three parameter model [2].

The current I_D passing in the diode is given by:

$$I_D = I_0 \left(e^{\frac{V}{mV_T}} - 1 \right) \tag{1}$$

I_0 is the reverse saturation current, m represents the diode ideality factor and V_T is the thermal voltage, which in turn is given by:

$$V_T = \frac{KT}{q} \tag{2}$$

K is the *Boltzmann* constant (K = 1,38 x 10^{-23} J/K), T is the cell's temperature in Kelvin and q is the fundamental charge (q = 1,6 x 10^{-19} C).

The current at the diode's terminal, *I* is thus obtained by:

$$I = I_S - I_D = I_s - I_0\left(e^{\frac{V}{mV_T}} - 1\right) \tag{3}$$

There are two operational points on the cell that have a special interest, which are the external short circuit and the open circuit. These give rise to two relevant parameters that are characteristic of each cell and are usually provided by manufacturers.

<u>External short circuit</u>

In this case, going back to the equivalent circuit, a set of conditions can be verified:

$$V = 0 \tag{4}$$

$$I_D = 0 \tag{5}$$

And so, joining equation (3) and (5), there comes:

$$I = I_S = I_{cc} \tag{6}$$

Where I_{cc} is the short circuit current.

<u>Open circuit</u>

$$I = 0 \tag{7}$$

Using equation (7) on equation (3), it results:

$$V = V_{ca} = mV_T \ln\left(1 + \frac{I_s}{I_0}\right) \tag{8}$$

Where V_{ca} represents the open circuit voltage. With equation (8) and (6) it can be obtained the reverse saturation current of the diode:

$$I_0 = \frac{I_{cc}}{e^{\frac{V_{ca}}{mV_T}} - 1} \tag{9}$$

<u>Standard Test Conditions</u>

It is known that the current generated by the photovoltaic cell depends on the incident irradiance as well as on the cell's temperature. In order to standardize the measurement of each photovoltaic cell's characteristics, manufacturers agreed on a set of standard test conditions (STC).

- Cell's temperature, $\theta^r = 25º\ C \equiv T^r = 298{,}16\ K$
- Incident solar irradiance, $G^r = 1000\ W/m^2$
- Solar spectral irradiance AM 1,5

With these reference conditions, it is possible to simulate the cell's operation resorting only to its manufacturer's information. This gives rise to new reference quantities.

$$V_T{}^r = \frac{KT^r}{q} = 0.0257\ V \tag{10}$$

Where V_T^r is the reference thermal voltage.

The expected maximum peak power produced by the cell at STC is given by:

$$P_{MP}{}^r = P_{DC}{}^r = V_{MP}{}^r * I_{MP}{}^r \tag{11}$$

Where V_{MP}^r and I_{MP}^r represent the maximum power voltage and current, respectively, at reference conditions.

<u>Maximum Power Output</u>

The output power at a given solar irradiance and cell temperature is derived from:

$$P = VI = V\left\{I_{cc} - \left[I_0\left(e^{\frac{V}{mV_T}} - 1\right)\right]\right\} \tag{12}$$

The maximum power is obtained when $dP/dV = 0$:

$$\frac{dP}{dV} = I_{cc} + I_0\left(1 - e^{\frac{V}{mV_T}} - \frac{V}{mV_T}e^{\frac{V}{mV_T}}\right) = 0 \leftrightarrow e^{\frac{V}{mV_T}} = \frac{\frac{I_{cc}}{I_0} + 1}{\frac{V}{mV_T} + 1} \tag{13}$$

It is now possible to obtain $V = V_{MP}$ and $I = I_{MP}$ that are solution to equation (13):

$$V_{MP} = mV_T \ln\left(\frac{\frac{I_{cc}}{I_0} + 1}{\frac{V_{MP}}{mV_T} + 1}\right) \tag{14}$$

$$I_{MP} = I_{cc} - \left[I_0\left(e^{\frac{V_{MP}}{mV_T}} - 1\right)\right] \tag{15}$$

Equation (14) can be solved numerically using MATLAB. With the solutions to equation (14) and (15) it is possible to obtain the maximum power, which can be given by:

$$P_{MP} = V_{MP} * I_{MP} = P_{DC} \tag{16}$$

At STC, $I = I_{MP}^r$, $V = V_{MP}^r$ and $P = P_{MP}^r$. These quantities, adding to V_{ca}^r and I_{cc}^r are characteristic of each photovoltaic cell and are provided by the manufacturer.

Returning to equation (3), which is valid for the operational points mentioned above, namely the external short circuit, open circuit and maximum power, and taking into account the reference conditions, it is obtained the following set of equations:

$$0 = I_s{}^r - I_0{}^r\left(e^{\frac{V_{ca}{}^r}{mV_T{}^r}} - 1\right) \tag{17}$$

$$I_{cc}{}^r = I_s{}^r \tag{18}$$

Applying to equation (15), it results:

$$I_{MP}{}^{r} = I_{s}{}^{r} - \left[I_{0}{}^{r} \left(e^{\frac{V_{MP}{}^{r}}{mV_{T}{}^{r}}} - 1 \right) \right] \tag{19}$$

Solving equation (17) with respect to I_0^r, it can be obtained the reverse saturation current at standard test conditions:

$$I_{0}{}^{r} = \frac{I_{cc}{}^{r}}{e^{\frac{V_{ca}{}^{r}}{mV_{T}{}^{r}}} - 1} \tag{20}$$

Another important quantity, which is considered independent from solar irradiance and the cell's temperature, is the ideality factor *m*. By inserting equation (20) in equation (19) and solving to *m*, it can be obtained:

$$m = \frac{V_{MP}{}^{r} - V_{ca}{}^{r}}{V_{T}{}^{r} \ln \left(1 - \frac{I_{MP}{}^{r}}{I_{cc}{}^{r}} \right)} \tag{20}$$

<u>Influence of real conditions</u>

This model considers a simplified influence of temperature and irradiance on the numerous described parameters. Given this assumption, it is acknowledged that the temperature affects the reverse saturation current, I_0, and the solar irradiance influences the short circuit current, I_{cc}, according to equations (21) and (22).

$$I_{0} = I_{0}{}^{r} \left(\frac{T}{T^{r}} \right)^{3} e^{\frac{N_{S}\varepsilon}{m}\left(\frac{1}{V_{T}{}^{r}} - \frac{1}{V_{T}} \right)} \tag{21}$$

T is the cell's temperature, N_s is the number of cells connected in series and $\mathcal{E}$ is the semi-conductor band gap ($\mathcal{E}$ = 1.12 eV for silicon).

$$I_{cc} = I_{cc}{}^{r} \frac{G}{G^{r}} \tag{22}$$

In equation (22), *G* is the incident solar irradiance.

One last assumption considered by this model is linked with the fact that the weather forecasts provide the external temperature and not the cell's temperature, which is used in calculations. Since the PV modules may operate at different conditions than the STC, it is important to determine the expected operating temperature of the cell's under said circumstances. The Normal Operating Cell Temperature (NOCT) is the temperature reached by the photovoltaic cell under the following conditions:

- Solar Irradiance = 800 W/m^2
- Air Temperature = 20º C
- Wind Velocity = 1 m/s

The NOCT is characteristic of each cell and is thus listed and provided by the manufacturer. The three parameter model takes only in consideration the solar irradiance and air temperature and it provides a correlation formula that relates the external weather conditions with the expected operating temperature of the cell:

$$\theta = \theta_a + \frac{G(\theta_{NOCT} - 20)}{800} \tag{23}$$

In equation (23), θ_a is the air temperature and θ_{NOCT} is the normal operating cell temperature.

Equations (14), (15) and (16), once obtained all the intermediary results, produce values for the maximum expected power for a given set of initial conditions.

Generation of electrical energy

After obtaining all the necessary quantities, both from consulting manufacturer's information and performing intermediate calculations, it was possible to generate results for the production of electricity from a set of photovoltaic installations.

Resorting to the weather forecast data mentioned above to gather hourly predictions for air temperature and solar irradiance, it was possible, using a MATLAB routine, to obtain the expected power output for every hour of a certain day.

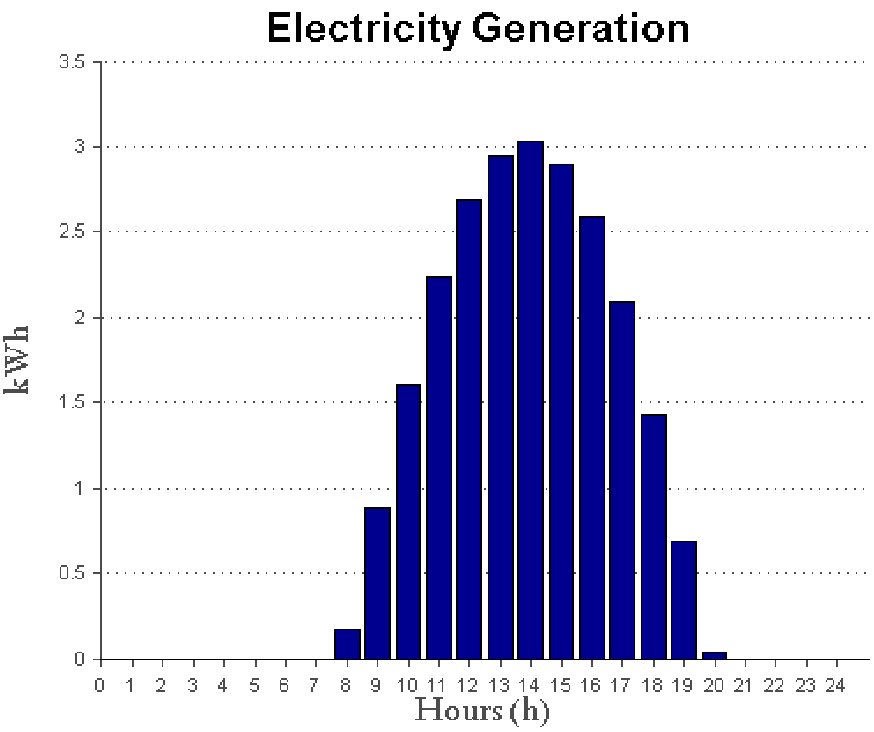

Figure 4.3: Expected generation results for August 30th from a 3.6kW installation.

On Figure 4.3 it can be seen the results for the production of energy for August 30th. It was considered an installation of 16 solar panels of estimated 230 W of peak power from a known manufacturer [59].

As expected, the amount of electricity varies with the increase in solar irradiance, as the maximum output is obtained at the hours of largest solar exposition, with no power produced during the night..

4.2.2 Consumption

This module was built using a set of data referring to the electricity consumption of a group of different domestic users. This data was obtained from a project on smart metering and energy efficiency called Smartgalp [60] and contains two different major profiles of electricity consumption. The first profile (**Profile A**) is from a situation where people are working at home, staying there permanently and the second profile (**Profile B**) is linked with a case where the house is empty during labour hours.

Eleven different individual sets of data were analysed and identified by matching the consumption patterns from **Profile A** or **B**, allowing to create an increased factor of variability on the consumption side.

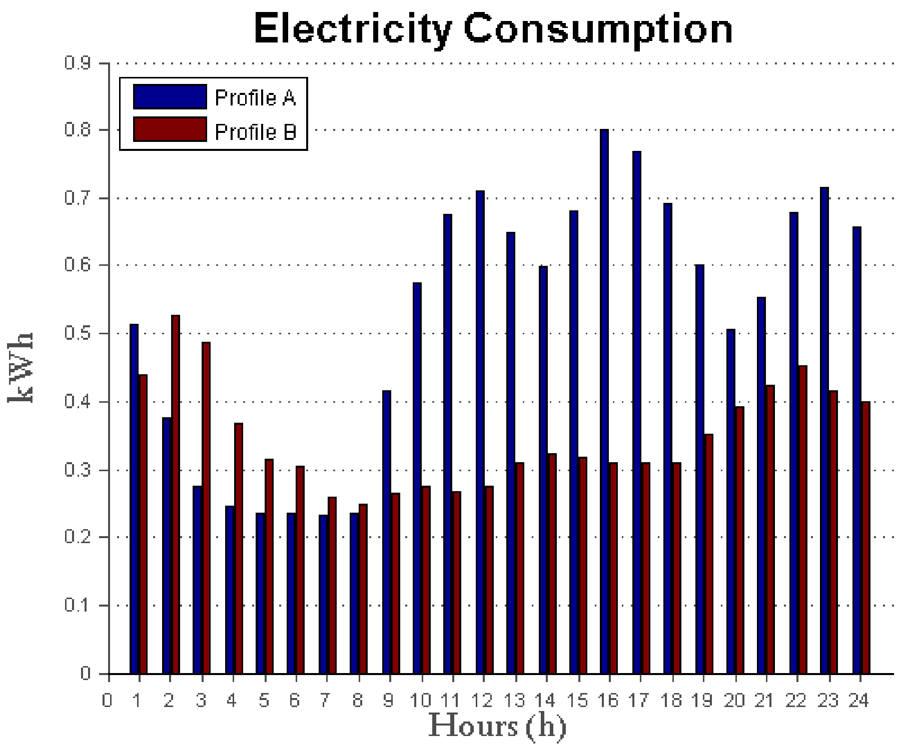

Figure 4.4: Comparative graph of the average hourly consumption for both profiles.

The available data was analyzed and a comparative hourly consumption for both profiles is presented in Figure 4.4, containing information relative to a year of consumption data. It can be seen that the **Profile A**, as expected, has higher values of energy expenditure per hour.

4.2.3 Market information

In this module, it was gathered data relative to both day-ahead and intraday market prices, from the OMEL website [11]. A MATLAB routine was prepared to execute the download of the market information relative to the set of days considered in the simulation program. The reason both market prices were used is explained in the next sub-chapter.

In Figure 4.5 it can be observed that the prices are higher for the periods when consumption hits its peak, during lunch hours (13:00 to 15:00) and at night (21:00 to 24:00).

In Figure 4.6, it is noticeable a trend in the intraday sessions prices. Considering the same hours to which electricity is negotiated, the prices tend to get higher as the deadline approaches, which is understandable as unbalances are pressured to be resolved in time. The first intraday market session was not considered in the development of this model, since that, in case of unbalances, the latest intraday session relatively to a given period is used to buy or sell the difference.

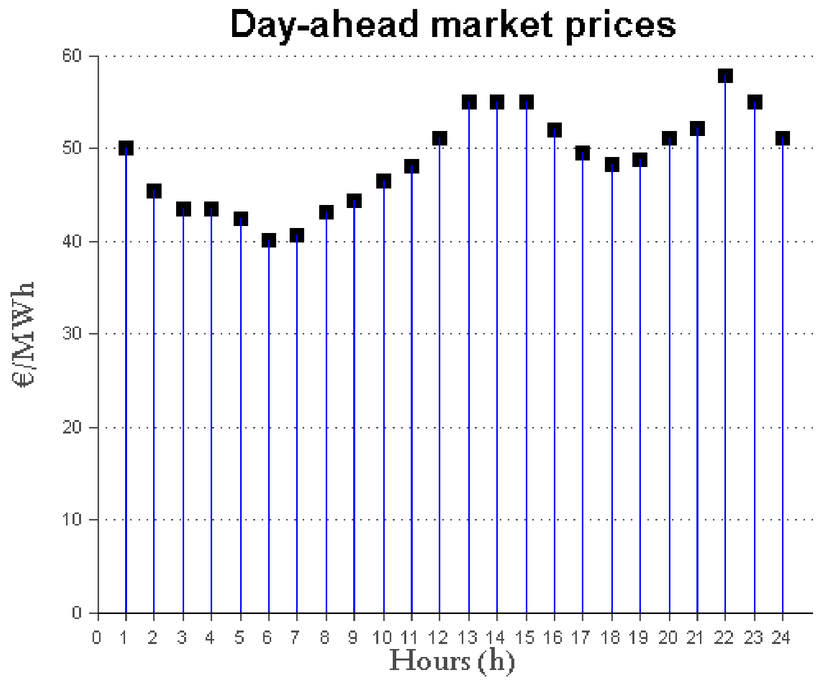

Figure 4.5: Day-ahead market prices for the 30th of August of 2014 [11].

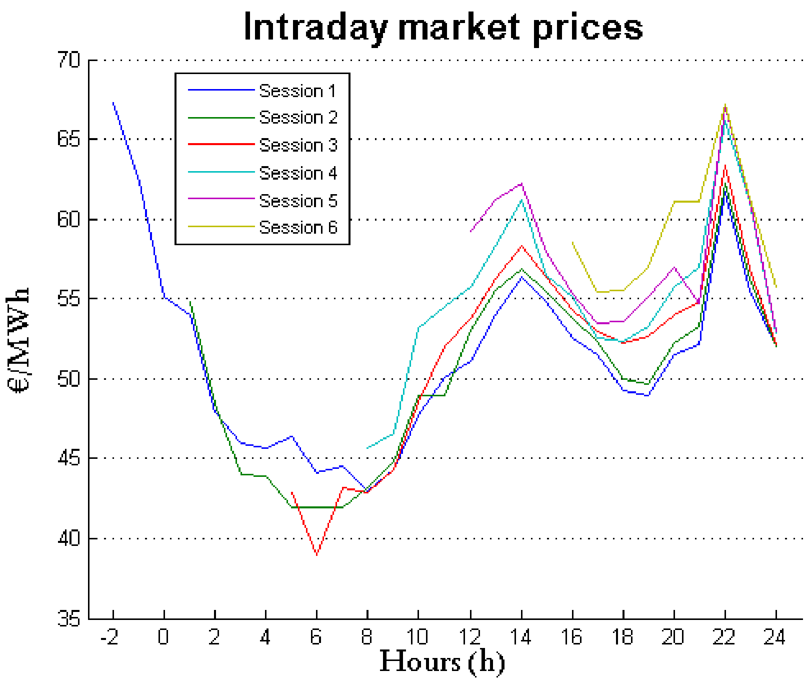

Figure 4.6: Market prices for the intraday sessions on the 30th of August, 2014 [11].

4.2.4 Simulator

In this sub-chapter it will be explained the main simulation routine operation, including generation and consumption, energy balance calculations and market resolution and solving unbalances.

Production: estimation vs actual generation

In the development of this project, it was not possible to obtain real generation data from production sites equivalent to the ones modelled by the mathematical model described. So, in order to create variability in the production module of the simulator, two different sets of power output prediction were obtained, based on distinct weather forecasts for the same day. For instance, prediction of electricity generation for day ***n*** is based on the weather forecasts of the day ***n-2*** for day ***n***. In the same way, the final production values, considered as real, are based on the weather forecasts of the day ***n-1***.

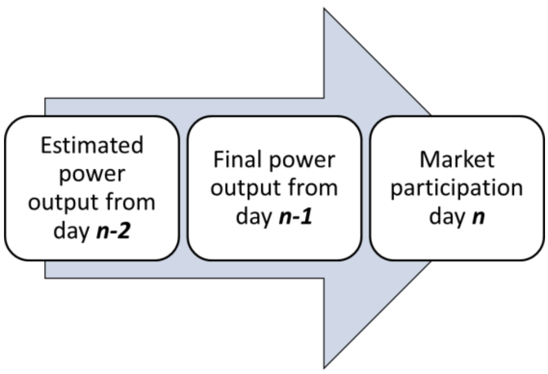

Figure 4.7: Description of the operation of the production module in the simulation routine.

This type of structured operation of the production module approaches closely the process described in chapter two, considering the participation in the day-ahead market, in which participants have to submit generation proposals for a certain day until the hour 10:00 of the previous day. The main difference resides in the absence of real production results and the subsequent need to use the last available weather forecasts as basis for the final power output. It should be stated that weather forecasts from day ***n*** cannot be used, as they only present information starting from the hour 12:00 of the same day, which makes them incomplete for calculations involving day ***n***.

Consumption: estimation vs actual consumption

Similarly to what happens in the production module, two different values of consumption are calculated in each case, in order to accurately represent a situation of participation in the market. An initial value, acting as a prediction of energy consumption for a given domestic producer is obtained from each of the two distinct production profiles previously presented. The total data was separated by seasons and subsequently, by weekdays, which allowed to identify and understand fluctuations arising from difference in climatic conditions and from work patterns. According to the chosen consumption profile, and given a certain day of the year, an expected value of energy consumption is created, based on these conditions.

Then, a second value for consumption is calculated, which will be considered as real and used in comparisons with the initial estimation. This second value is based on the eleven individual sets of values, grouped in the two general profiles, containing information relative to a year worth of energy consumption. In this part, given the chosen profile and day of the year, the simulator will randomly pick one of the available individual consumption data sets for that profile and obtain the power consumption from the same weekday of the same week as the considered day.

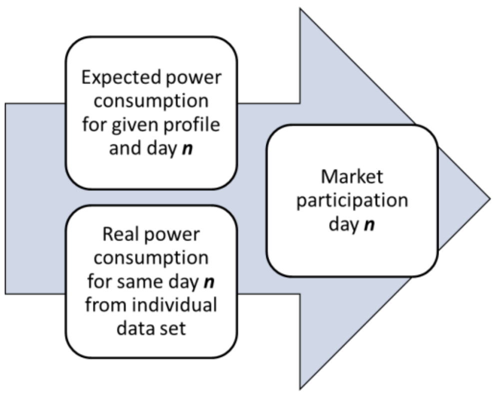

Figure 4.8: Description of the operation of the consumption module.

The expected consumption value is used together with the estimated power output to provide a prediction of the available energy. Similarly, the real consumption and production values give the definite quantity for the available energy traded in the market, as it will be described later in the document.

Energy Balance Calculations

As described previously, in this project it is considered that the aggregated power traded in the electricity market corresponds to the net value of available energy. For that matter, it is important to obtain the energy balance in all situations, given by the amount of power produced minus the amount of power consumed in the same time period, as it can be seen in equation (24).

$$EB_{x,y} = P_{x,y} - C_{x,y} \tag{24}$$

Where $EB_{x,y}$ is the energy balance for the hour y of the day x. P and C are the production and consumption values considered for the same period, respectively. For market trading purposes, only the cases when $EB_{x,y}$ is positive are eligible for participation.

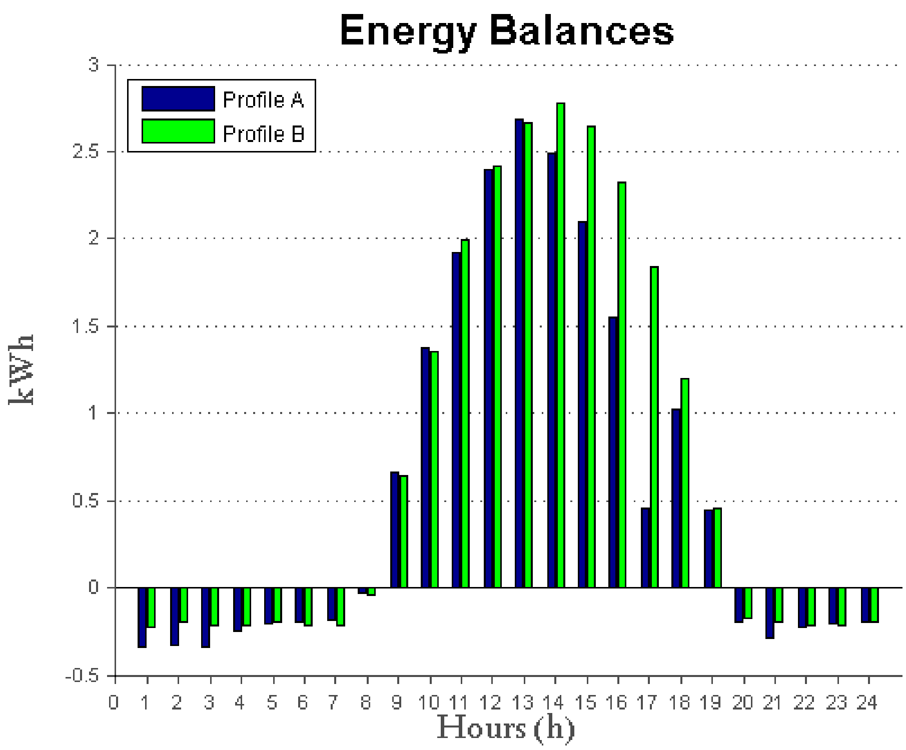

Figure 4.9: Energy balances for the 30th of August and considering both consumption profiles.

As expected, the energy balance pictured in Figure 4.9 is negative during the night and low productive periods. Also, there is a noticeable difference in the amount of energy available for market trading between the two profiles. Profile B, relative to the case where the house is unoccupied during the day, is likely to present better results in the selling of power as it is able to sell more of the same produced electricity.

Market resolution and solving unbalances

As mentioned earlier, the prediction for the amount of available electricity for a given time period submitted to the operator for participation in the day-ahead market is based on the initial values of power output and consumption. These are the values producers set themselves to deliver. However, attending to the unpredictable nature of solar PV production, unbalances are possible to occur. A definite amount for the available electricity, based on the final estimations for production and consumption is then submitted and compared to the initial one. Then, in the case of fluctuations between the contracted amounts and the delivered ones these are solved with resource to the several intraday market sessions.

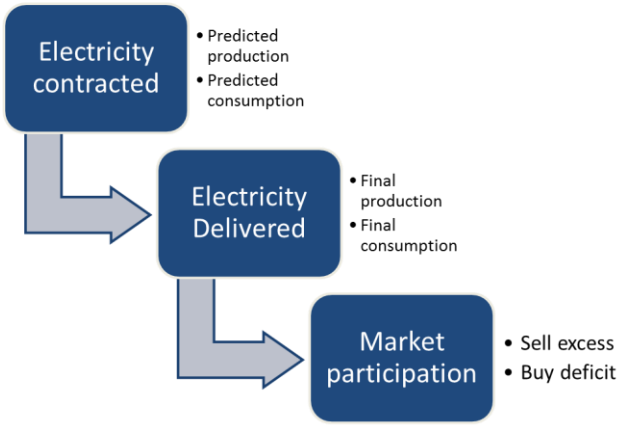

Figure 4.10: Description of the market resolution operation.

As Figure 4.10 depicts, from the comparison between the delivered electricity and the contracted electricity rises the need to solve the differences in order to properly fulfill the agreement on the amount of traded power.

The electricity agreed to be traded at a given period is to be sold at the price offered in the day-ahead market. However, if the electricity delivered does not match the amount contracted, the difference is solved with participation in the latest intraday-session, whose closing periods are described in chapter 2. For instance, if for the hour 13:00 of a given day it was agreed to be traded 5 kWh of electrical energy and only 4.5 kWh were actually delivered, then those 4.5 kWh are sold at the price done at the day-ahead market. The 0.5 kWh missing to reach the agreed amount is bought at the latest intraday session for that period, which in this example would be the 5^{th} session. In this case, the producer would not be able to reach the expected revenue for the initial 5 kWh contracted, as the energy missing would have to be bought at his expenses. In an opposite scenario, if from the same 5 kWh agreed, the producer delivered 5.5 kWh for the same given time period, only the agreed amount would be sold at the day-ahead price, even if that might represent a loss or gain, when compared with the intraday prices. The 0.5 kWh in excess would be sold in the latest intraday session. The producer would have greater revenue than expected, but it could have been even higher if he had had a better estimation of the power he would be able to deliver.

With the aid of these two scenarios, it was explained the main functioning of the market resolution in this simulator, as well as the mechanism that allows to solve the unbalances produced by the uncertainty in both production and consumption sides. In any case, the sales value obtained at each period of one market session is given by equation (25):

$$S_{x,y} = EB_{x,y} \times P_{D_{x,y}} + dEB_{x,y} \times P_{ID_{x,y}} \tag{25}$$

As the expression above shows, the result for hour *y* of a given day *x*, $S_{x,y}$, is a sum of the activity in the daily market, represented by the energy balance delivered $EB_{x,y}$ multiplied by the session price $P_{Dx,y}$, and the activity in the intraday market where the remaining energy balance $dEB_{x,y}$ is sold or bought at intraday session price $P_{ID,x,y}$.

4.3 Parameters selection

In this section it will be described the configuration of the main parameters of the simulator including the number of clients considered, number of solar panels per client and the type of panel owned.

4.3.1 Number of clients

The number of clients considered in each simulation routine will not be an input variable. Since there is only one location for which it is gathered weather information, the number of clients acts mainly as a scaling factor. It was chosen **100** as a reasonable value for this parameter. This will generate a significant amount of data, without compromising the efficiency of the simulation.

4.3.2 Number of panels per client

Under the legislation on the micro-generation regime in Portugal described in Decreto-Lei n.º 25/2013 [61], the limit for the installed capacity (kW) for privately owned PV operations stands in 5,75 kW. However, the subsidized regime in which most micro-producers were incorporated has a lower limit of 3,68 kW. In order to adapt the simulator to the vast majority of the real players, the number of panels reflected per client is **16**. Considering that each solar panel has an estimated maximum power of 230 W, the total installed capacity in each client will be 3,68 kW.

4.3.3 Type of panels owned

In the development of this work, it was considered only one type of solar panel manufacturer in order to reduce the amount of variables under study. By stabilizing this parameter it is possible to better analyze the effect of more important aspects, such as the consumption profile or production under different weather conditions. Fluitecnik [62] was the chosen manufacturer and from the range of offered products, the following model was picked: Fluitecnik FTS-220P – 230W [59].

Technical features	Fluitecnik FTS-220P 230W
Peak Power [W]	230
Maximum power current [A]	7.73
Maximum power voltage [V]	29.63
Short circuit current [A]	8.46
Open circuit voltage [V]	37.1
Normal operating temperature [ºC]	46
Temperature coeficient at I_{cc} [A/K]	0.0051
Temperature coeficient at V_{ca} [V/K]	-0.1224
Number of cells	60
Lenght [m]	1.653
Width [m]	0.990

Table 4.1: Technical features of the two distinct types of solar panels considered.

4.4 Simplifications of the model

Since this is an experimental academic project with the purpose of simulating the activity of a virtual power plant in the electricity market, a few assumptions have to be made in order to increase the practicality and reduce the complexity of the model. It is expected that these simplifications do not alter the simulation results in a significant way.

4.4.1 Virtual Power Plant as a price taker

Since the total amount of electrical energy a VPP may take to the market represents only a small fraction of all the electricity traded, the VPP is limited to sell at the price offered in each particular session. In other words, the absence of a significant market share, a common feature to most of the producers from renewable sources of energy, removes them of the ability to influence market price, hence leading them to participate as price takers.

Having set this premise and keeping in mind that the VPP plays the part of an intermediary in the market, it comes as a subsequent assumption that by accepting the market price the VPP is able to sell the entire amount of electrical energy made available at said price.

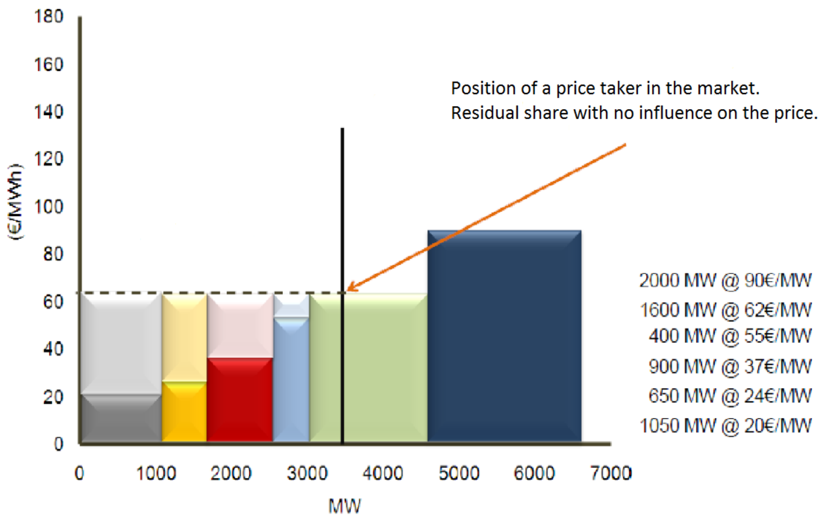

Figure 4.11: Position of a price taker player in the electricity market. Adapted from [12].

As Figure 4.11 shows, the VPP will occupy a position with reduced share selling at market price. Concluding, it will be set as certain that the entire amount of electricity made available will be sold at the price specified for the given market session.

4.4.2 Only two consumption profiles

In the absence of additional data from consumption side information but also having in mind the relative low complexity of this simulator, it was decided to have only two major profiles. Despite being a significant generalization, since each individual home has its consuming patterns, this assumption has a mitigation factor. As explained earlier in the chapter, both of these two consumption profiles are each represented by a group of distinct sets of data which allows to increase variability in the results, but maintaining the intended simplicity of the project.

4.4.3 No price penalties

As described in the market resolution section, when differences occur between the estimation of available electricity and the actual electrical energy delivered in the market, the gap is fixed by participation in the latest intraday market session available for the hour at which the situation respects. The result of trading in the intraday session, whether having a positive or negative effect, will be regarded as final and no penalties will be applied to the VPP.

4.4.4 No operational costs

The purpose of the model developed in this project is to simulate the activity of a VPP in the electricity market in a simple manner, including only the aggregation of the available energy from the clients to the trading in day-ahead and intraday sessions. No operational costs of running the structure of a VPP are considered in this model, since the financial viability of running said structure is not part of the scope of this study.

5 Presentation of results and analysis

5.1 Test description

In this section, the tests performed with the simulator developed in this project will be described regarding its goals and operation. The simulation is programmed to run with two distinct sets of information relative to **21** straight days. The first between the August 17th and September 6th of 2014 and the second one between February 2nd and February 22nd of 2015, one with data regarding the summer season and the other covering the winter time settings.

The tests performed by the simulator are listed below:

- Market results considering Summer and Winter periods and the consumption profile of the individual owners;
- Error tendency and composition;
- Model application in comparison to current legislation on privately owned PV generation.

This diversified assessment is aimed at analysing the effects of some of the most important aspects of a solar PV project in the market operation results. The influences of the generation and consumption sides and the variability in the results over the course of a day are the main subject of the following tests. Additionally, the comparison of the model's results with the Self-consumption regime [57] alternative aims at analysing the advantages or disadvantages provided by the application of this project's simulator. A more detailed description is provided in the next subchapters.

5.1.1 Market results

This test will focus on the results provided by the two distinct sets of data, considering both consumption profiles. It will be analysed the generation output as well as the consumption information and finally the market results. Differences in the number of productive hours and in the consumption patterns between the two seasons are studied in this test, but fluctuations in market prices are also examined. It will also be analysed the influence of the distinct consumption profiles of the producers on the market results.

5.1.2 Error tendency and composition

Through this test, it will be analysed the variability of the market results on different periods of the session, namely the existence and composition of any sort of error tendency present in the model's operation. The goal is to study the behaviour of the simulation model using weather forecasts to predict generation output during the course of a day. It will be evaluated which periods are more prone to present estimation errors and which correspond to more reliable results. This sort of test is interesting in the VPP operator point of view, as it may provide information on how to best manage the amount of available energy during the course of a day.

With various sets of parameter configuration, varying the consumption profile of the individual producers, the tests will focus on the precision of the predictive model created in this project to obtain generation data through weather forecasts.

5.1.3 Model application

In this test, it will be analysed the average revenues per client per day obtained through the VPP model developed in this project in comparison to what it would be the market result using the alternative Self-consumption regime, described in Decreto-Lei Nº 153/2014 [57]. Under this legislation, privately owned generation installations with maximum power output under 1 MW injecting into the grid are remunerated according to the following expression:

$$R_m = E_m \times OMEL_m \times 0{,}9 \tag{26}$$

Where R_m is the revenue obtained at month *m*, E_m is the sum of the electrical energy traded in month *m* and $OMEL_m$ is the average day-ahead price practiced in that month. The interpretation of the legislation is done in order to allow a proper correspondence with the model developed in this project. And so, the revenue obtained in a given month, R_m , will be computed as the sum of the revenues of all periods of all days in said month, through the following expression:

$$R_m = \sum_{x,y=1}^{n} R_{m_{x,y}} \tag{27}$$

Where *n* is the total number of periods in month *m.* Also, the energy taken to the market in a given month, E_m, will be obtained using the same method:

$$E_m = \sum_{x,y=1}^{n} E_{m_{x,y}} \tag{28}$$

Finally, the average day-ahead price of a month *m,* $OMEL_m$, will be obtained as the average of all the periods of all days in month *m,* by the following expression:

$$OMEL_m = \frac{\sum_{x,y=1}^{n} P_{x,y}}{n} \tag{29}$$

It is expected from the results of this application that the average market result per client per day should be higher using the VPP model designed in this project, when comparing to the alternative remuneration system.

5.2 Data acquisition and treatment

After running the simulator for the two separate sets of data and considering both consumption profiles, four distinct groups of results were obtained:

- Summer conditions with consumption profile A;
- Summer conditions with consumption profile B;
- Winter conditions with consumption profile A;
- Winter conditions with consumption profile B.

All sets of results were subject to the same conditioning and treatment in order to extract coherent conclusions from the project. As a common standard, it was considered for analysis the aggregate results of generation, consumption and balance of the whole set of clients. This assumption is taken with the intent of projecting the results from the point of view of the VPP operator, and not from the individual owner perspective. For that matter, the quantities considered for calculations in each set of results are given by the following equations:

$$P_{x,y} = \sum_{i=1}^{n} P_{i_{x,y}} \tag{30}$$

$$C_{x,y} = \sum_{i=1}^{n} C_{i_{x,y}} \tag{30}$$

$$B_{x,y} = \sum_{i=1}^{n} B_{i_{x,y}} \tag{32}$$

Where $P_{x,y}$, $C_{x,y}$ and $B_{x,y}$ are the generation, consumption and energy balance amounts of the set of clients for day x and period y, respectively, $P_{i_{x,y}}$, $C_{i_{x,y}}$ and $B_{i_{x,y}}$ are the individual clients' quantities and n is the number of clients.

For the presentation of results, in what respects to the quantities named above and additionally to the day-ahead market prices and market trading results, the average values for each period and for each day were obtained through the following formulas:

$$\bar{x}_y = \frac{\sum_{x=1}^{d} x_{x,y}}{d} \tag{33}$$

Where $\bar{x}_y$ is the average value of generation, consumption or energy balance for the period y for the set of clients, x_y is the value for a given day and d is the number of days of the simulation.

$$\bar{x}_x = \frac{\sum_{i=1}^{d} x_x}{d} \tag{34}$$

Where $\bar{x}_x$ is the average value of the quantity for a whole day of the set of clients and x_x is the value for day x, the sum of the generation of all periods in a day, given by:

$$x_x = \sum_{y=1}^{24} x_{x,y} \tag{35}$$

Standard deviations for the average values computed above were also calculated. The following expressions were used:

$$\sigma_{x_y} = \sqrt{\frac{\sum_{x=1}^{d}\left(\bar{x}_y - x_{x,y}\right)^2}{d}} \tag{36}$$

$$\sigma_{x_x} = \sqrt{\frac{\sum_{i=1}^{d}(\bar{x}_x - x_x)^2}{d}} \tag{37}$$

The value σ_{x_y} is the standard deviation for $\bar{x}_y$, the average value for period y and σ_{x_x} is the standard deviation for $\bar{x}_x$, the average value per day.

This average and standard deviation analysis is useful to understand how the generation, consumption and consequently, energy balance and market results fluctuate on the course of the set of days. The value for standard deviation is predicted to be significantly high for generation results, due to the fact that are being considered for calculations both sunny and rainy days, whose solar irradiance values may vary from almost 1000 W/m$_2$ at a given period in the first case down to between 100 and 200 W/m$_2$ for the same period of a different day.

To complement this analysis, it was also obtained, using MATLAB functions, graphical representations of the median, 25th and 75th percentiles and the values beyond which results are considered as outliers. These last correspond to the 0.35th and 99.65th percentiles or approximately $\bar{x}_y \pm 2.7\sigma_{x_y}$. This additional study, performed on results for generation, consumption, day-ahead prices, energy balance and market outcomes, allows the analysis of the dispersion of results and the identification of the resulting values that vary the most relatively to the computed average. Nonetheless, results considered as outliers are included in the overall analysis, since they represent a common occurrence relative to the uncertainty of climate conditions.

Error tendency and composition

For this analysis it was computed the accumulated energy balance error for each period, over the course of the 21 day set of days using the following expression:

$$EBe_y = \sum_{x=1}^{d} EBe_{x,y} \tag{31}$$

Where EBe_y is the cumulative energy balance error for period y and $EBe_{x,y}$ is the energy balance error for period y of day x. In a similar manner, the accumulated market result error is obtained for each period, considering the whole set of 21 days:

$$MRe_y = \sum_{x=1}^{d} MRe_{x,y} \tag{32}$$

where MRe_yrepresents the cumulative market error for period *y* and $MRe_{x,y}$ is the market result error for period *y* of day *x*.

For the energy balance composition as well as the market result composition, results were obtained through by computing separately the averages and standard deviations of the contributions of each part. Generation and consumption errors in the case of the energy balance and expected market result, real market result, result of participation in day-ahead market and result of intraday market. Equations (33)-(37) were used in these calculations.

Model application

For this analysis, in order to achieve equal test conditions for both remuneration formulas, the total amount of energy balance was computed through equation (27). Then, in the case of the Self-consumption regime, it was applied equation (26) to the energy balance corresponding to each month using the average day-ahead price obtained through equation (29). In the case of the summer set of data, there were two parts corresponding to the September and August days, and so, the total revenue per client in the 21 day period would be the sum of the partial revenues relative to each month. Regarding the VPP model, in order to obtain the total revenue per client per day, it was used equation (25) applied to each individual owner.

The average values of revenue per day and the correspondent standard deviations for each remuneration form where obtained through equations (33)-(37) applied to the set of 100 clients.

5.3 Results of the simulation model

In this section, the results of the different tests are presented and described.

5.3.1 General results

Before entering in the analysis regarding the set of conditions and parameters presented above, it is most helpful to present the general results obtained through the simulation model. These include generation and consumption for both periods as well as the day-ahead market prices practiced in those same periods.

Generation data

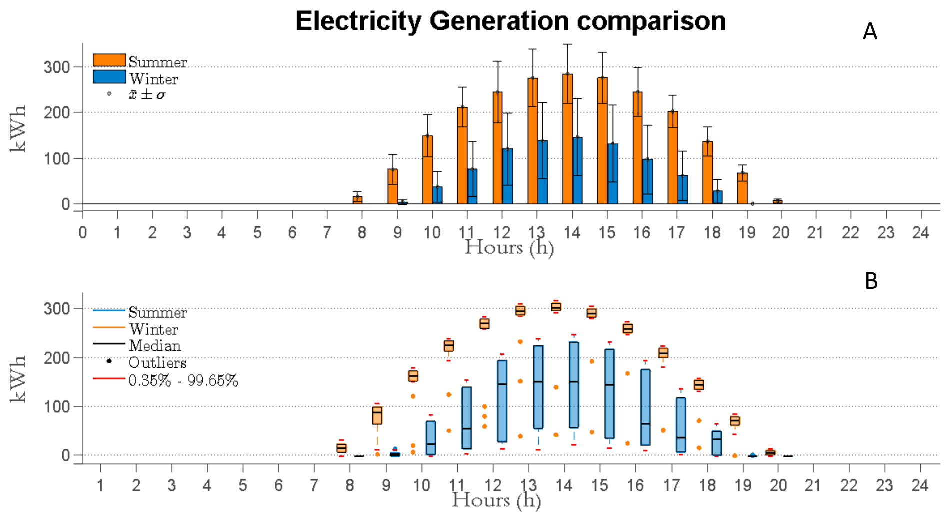

Figure 5.1: Average electricity generation comparison for both periods

It can be seen in plot A the average and standard deviation representation of the results as plot B shows the median and interquartile demonstration. As expected, the average amount of electricity produced per day is significantly higher during the summer period, when comparing with the winter period. The higher and more constant values of solar irradiance during the summer and the longer solar exposition are the main reason behind this difference. Figure 1.1 shows the smaller standard deviation values and shorter interquartile ranges obtained for the summer period data as well as the larger number of outlier points, confirming the smaller variance in generation output. Comparing both data representations, it is visible that the median value of results is higher than the average result, which can be confirmed by looking at Table A.1. This is due to the fact that the most probable results, corresponding to sunny days, allow to obtain significantly higher values of generation than the less likely cloudy days, represented by the outlier points, while these last ones contribute to lower the average values.

Average Generation kWh	Summer	Winter
	2178,64 ± 488,29	834,99 ± 512,45

Table 5.1: Average generation results per day for both periods.

As Table 5.1 shows, the average generation per day in during the summer period is more than double the value for the winter data. On the contrary, the standard deviation for the winter data is larger than for the summer. This is due to the greater number of cloudy days in the winter, which lowers the average generation values, and to the higher relative weight that these results have during the winter period, which raises the standard deviation values.

Consumption data

As for consumption, the set of information obtained considering both profiles for the summer and winter periods, respectively, are pictured in the figures below.

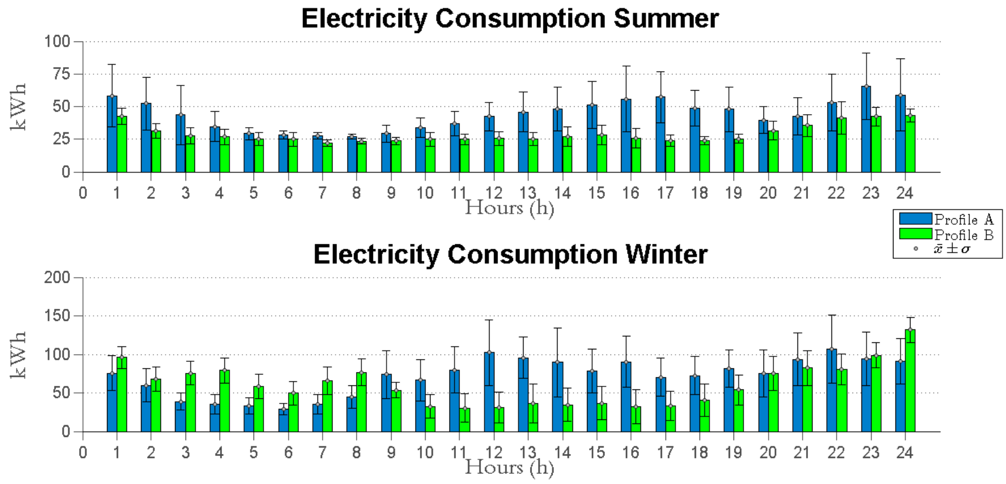

Figure 5.2: Average electricity consumption of the set of clients for both periods.

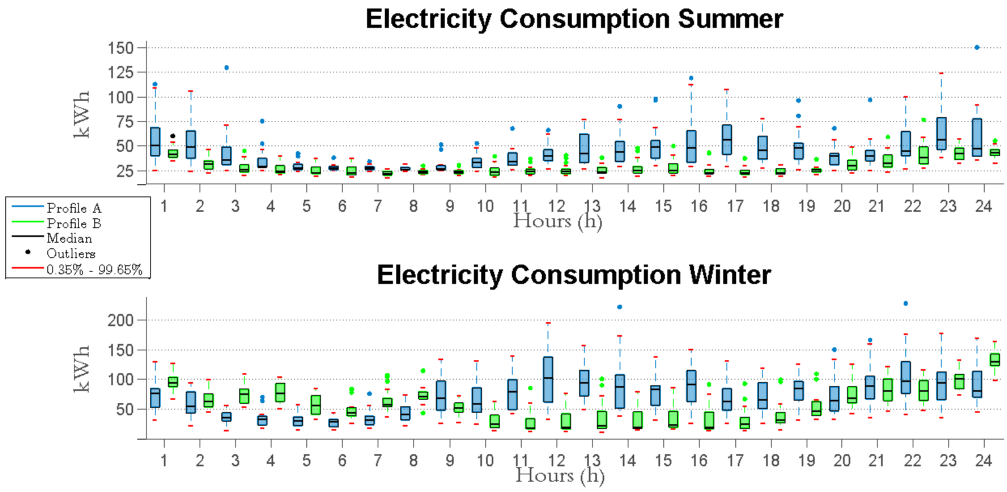

Figure 5.3: Average electricity consumption. Median and interquartile representation.

In Figure 5.2 and Figure 5.3 it can be seen as predicted that clients from Profile A, corresponding to houses occupied during day time, have higher values of consumption during most of the periods during a day. Only in the some night periods and during the winter, clients from profile B present larger values of consumption. It can also be observed that consumption during the winter period is higher than in the summer for both periods, which is a natural response from clients to the lower temperatures and less number hours of sun light. The greater number of different individual sets of data from profile B would lead to expect a higher value for the standard deviation, which does not occur. Results from profile A have also greater interquartile ranges, which means they are less precise and will more likely lead to less precise energy balances. More detailed results can be seen in Table A.2 and Table A.3.

Average Consumption (kWh)	Summer	Winter
Profile A	1057,99 ± 221,69	1712,45 ± 388,13
Profile B	696,95 ± 53,25	1453,08 ± 278,32

Table 5.2: Average consumption results per day for both periods.

Results shown in Table 5.2 confirm the graphic representation of the set of data, with consumption being higher in the winter than in the summer and also for clients from profile A over profile B.

Day-ahead market prices

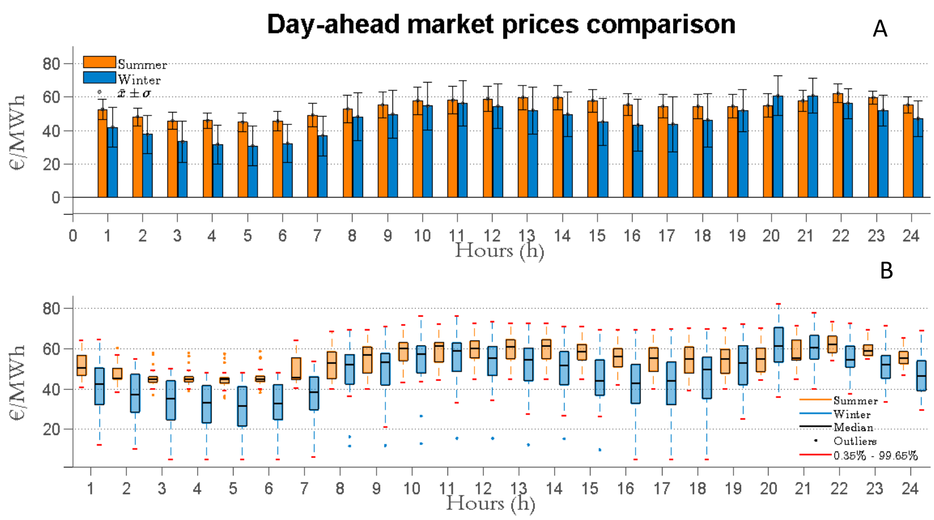

Figure 5.4: Average day-ahead market prices comparison for both periods.

Again, plot A shows the average and standard deviation representation of the results as plot B shows the median and interquartile demonstration. As seen in Figure 5.4, day-ahead market prices tend to be higher in the summer period during most hours of the day, with exception for the 20th and 21st periods. These two periods match the time of the day during which most people are at home, still active and consuming. The higher demand for energy in these periods in the winter may explain the difference in price. On the other hand, between the 1st and 7th hours, the price of energy in the winter tends to be significantly lower, which may be explained by the higher predominance of electricity from renewable sources in the grid (wind and hydro) during the nighttime. Prices for the winter have in general larger standard deviations and longer interquartile ranges, meaning that they vary more during the set of days. More detailed results can be seen in Table A.4.

Average day-ahead price (€/MWh)	Summer	Winter
	53,89 ± 6,50	46,21 ± 12,68

Table 5.3: Average day-ahead market prices for both periods.

Results in Table 5.3 confirm the higher prices for day-ahead market during the summer and the larger standard deviation values for winter data.

5.3.2 Market results analysis

The results for the available energy and market outcomes analysis, considering both sets of data and consumption profiles of the individual producers can be pictured in the figures shown below.

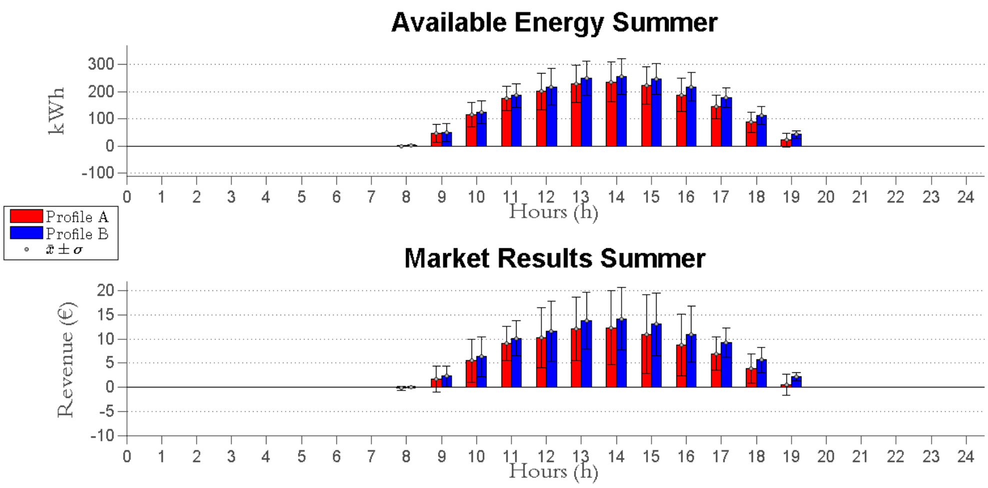

Figure 5.5: Available energy and market results for the Summer period.

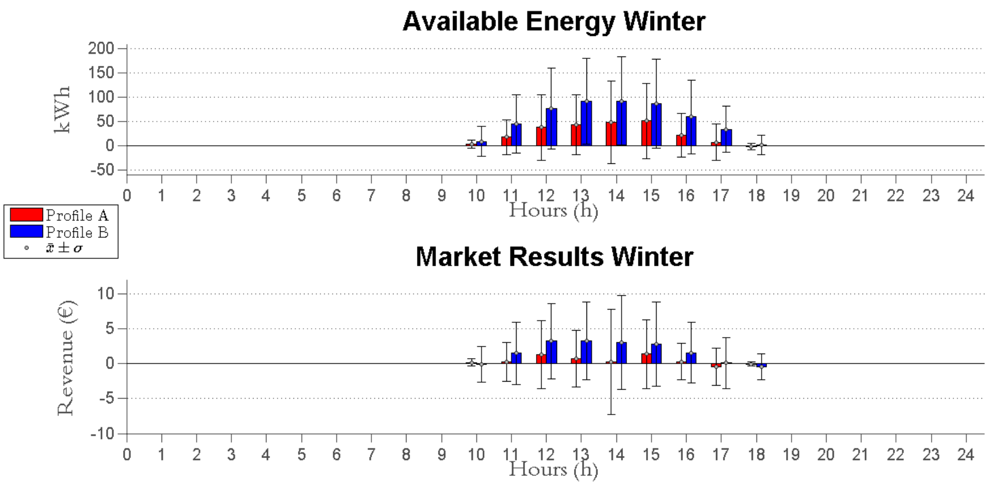

Figure 5.6: Available energy and market results for the Winter period.

When comparing the results considering consumption profiles, the outcome is as expected from the analysis of the consumption data. Clients from profile B tend to have slightly more available energy for market trading, which leads to higher revenues from participation in the market. As estimated in the analysis of general results, outcomes for clients from profile B have larger fluctuations in most hours of the day for the set of data relative to the summer. Winter results, as noted above present variations too significant to be considered as solid results. These variations are fuelled by the large relative deviations induced by having more cloudy days in a set of data with lower average solar irradiance.

When analyzing results from the two different sets of data relative to the summer and winter, it is clear in Figure 5.5 and Figure 5.6 that available energy for both profiles is significantly higher during the summer period. Subsequently, results from the market trading follow the same trend and are higher in the summer as well. It should be noted that results from the winter data present a large variability with the standard deviation being larger than the value itself for most periods. This can be explained by the higher fluctuation in the results of generation, consumption and prices, observed in the section above.

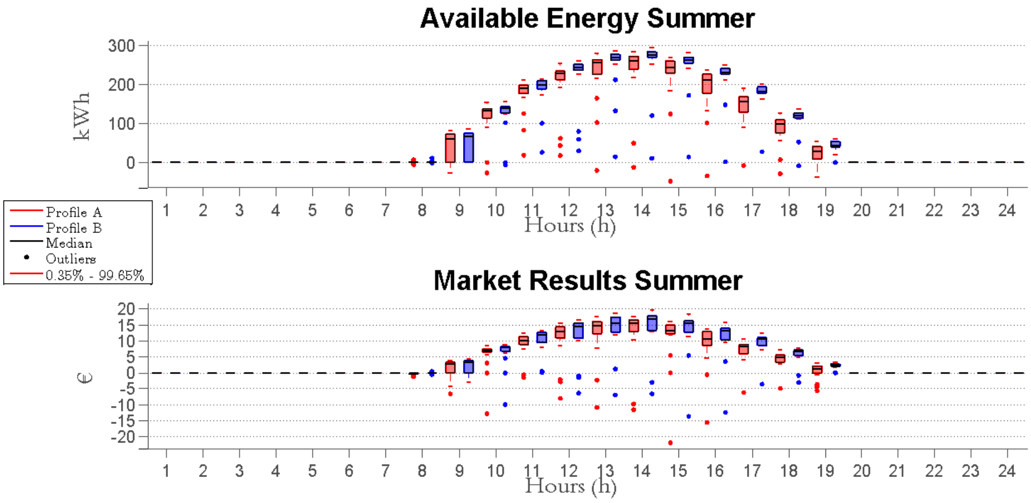

Figure 5.7: Summer period results. Median and interquartile representation.

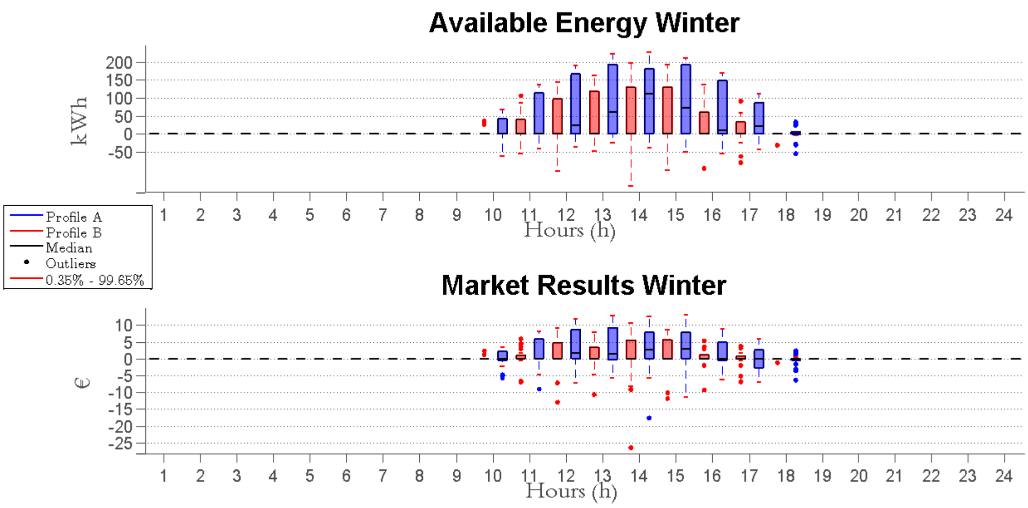

Figure 5.8: Summer period results. Median and interquartile representation.

Analyzing the median and interquartile representation of the market results it can be observed the longer interquartile ranges of the winter results, when compared to the summer results, coherent with the large standard deviations detected in Figure 5.5 and Figure 5.6. The existence of a significant amount of outliers in these results is consistent with the ones observed in the general results of generation and consumption. Some of the outliers in Figure 5.7 have a negative value, which means that some periods during the two sets of data present negative final energy balances forcing a sole buying activity in the corresponding intraday session, contributing for the appearance of negative outliers in Figure 5.8. More detailed results can be seen in Table A.5, Table A.6, Table A.7 and Table A.8.

Model results	Summer		Winter	
	Profile A	Profile B	Profile A	Profile B
Available Energy (kWh)	1662,65 ± 518,81	1879,02 ± 462,36	228,93 ± 352,67	494,83 ± 528,81
Market results (€)	82,26 ± 46,25	99,73 ± 40,85	3,89 ± 22,32	14,94 ± 32,80

Table 5.4: Average results per day for available energy and market results.

Results from Table 5.4 confirm the graphical analysis, with higher outcomes for clients with consumption profiles of type B and for the summer period.

5.3.3 Error tendency and composition

Available energy

For this test it was computed the accumulated error for the set of days between the expected available energy and the amount that was delivered to the market. Results are shown in the figure below.

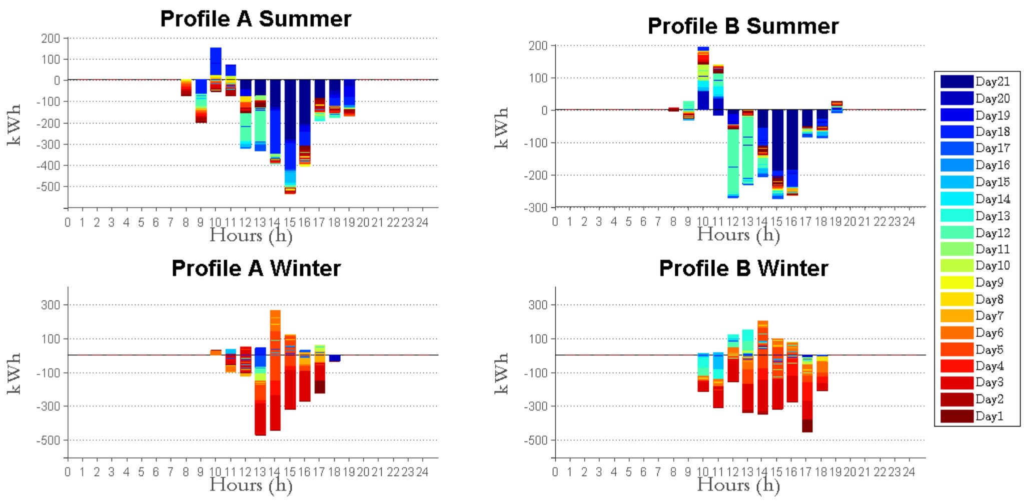

Figure 5.9: Accumulated error between the estimated and delivered available energy.

From the analysis of Figure 5.9, it can be seen that the simulator developed in this project tends to overestimate the amount of available energy taken to the market, as the accumulated error appears to be negative in most periods of the day. It can also be observed that the contribution of some days to the total error is quite significant, symptom of unpredictable major fluctuation in results. An example of that is the contribution of day 21 in the 15th and 16th hours in the summer results. The 10th, 11th and 19th hour of the day for profile B in the summer period present the only positive error tendencies, as the 15th period appears to be the most prone to negative variance. As for the winter period, results are less clear. First of all, there are missing results relative to some periods of some days, simply because there was no available energy predicted or delivered and hence, no error. Second, because being a representation of cumulative error values, results with opposite tendencies will overlap with the final result being the latter one, which, due to the operation of the simulator, corresponds to the day 1. The numerical results can be seen in Table A.9.

Market results

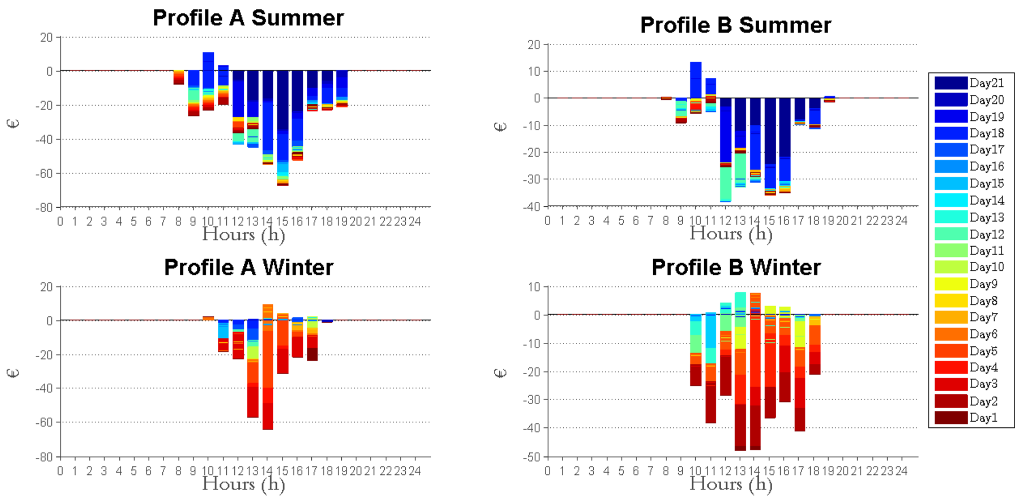

Figure 5.10: Accumulated error between the estimated and actual market outcome.

As expected, since market results are a direct consequence of the available energy taken to the market, the error tendency of the commercial activity pictured in Figure 5.10 is a close depiction of the error tendency of the available energy. The only major difference is the fact that no period in the four different sets of data is able to present a positive final result in the cumulative market error, considering the positioning of day 1's result as the final aggregated result. This is motivated by the participation in the intraday market sessions, the market resolution operation chosen for the simulator in this project. Significantly lower intraday prices reduce the positive effect of selling surplus in generation output, while higher prices might aggravate losses when buying energy to compensate production deficits. The numerical results can be seen in Table A.10.

Available energy error composition

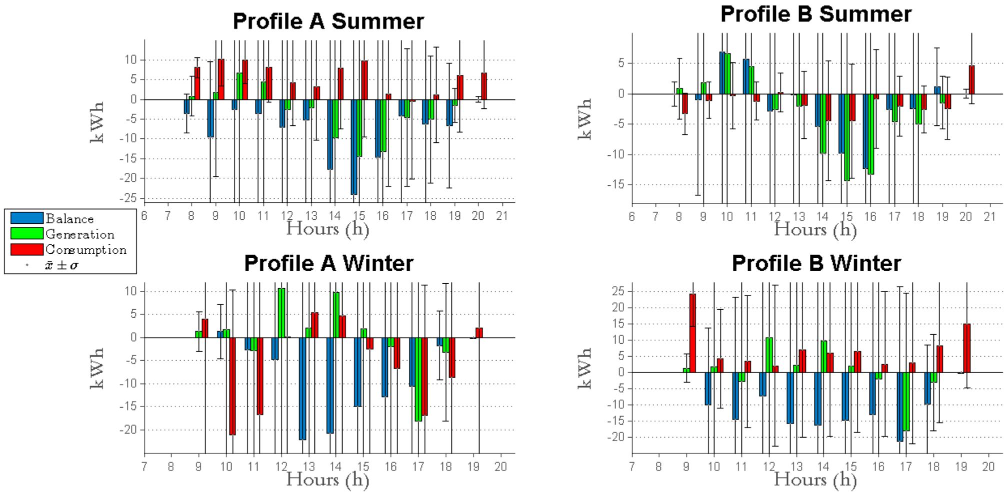

Figure 5.11: Representation of the average energy balance error composition by source.

In Figure 5.11 it can be observed the composition of the average energy balance error for each hour of the different sets of data. It should be noted that a positive value in the generation error has a positive impact in the energy balance, while a positive value in the consumption error has a negative influence in the energy balance.

In blue color, the overall energy balance error appears to be consistent with the data shown in the previous graph, with the only periods with positive average errors being the 10th and 11th hours for profile B in the summer period. For the summer data, the average generation error is positive until hour 12, from which it starts to take a negative value. As for the winter data, the average generation error is less significant, with exception for the 12th, 14th and 17th in which it reaches a larger amount. When analyzing consumption average errors, it can be seen that for the summer data, profile A and profile B have opposite behaviors, with the first one showing a tendency for underestimating the consumption of energy while the second one appears to consume less than predicted during most periods of the day. In the winter, profile B reverses its variation, as it appears to consume more than the estimated value, while profile A presents a general negative error tendency, particularly in the 10th, 11th and 17th period.

It should be stated that for the majority of the results regarding overall balance, generation and consumption, the standard deviation is significantly higher than the value itself, depriving the outcome of the simulator from the background of a solid statistical result. In fact, only in the outputs of the set of data relative to the summer it is possible to verify the approximation of the average overall error to the combination of the average generation error with the average consumption error. More detailed results can be seen in Table A.11 and Table A.12.

Market results composition

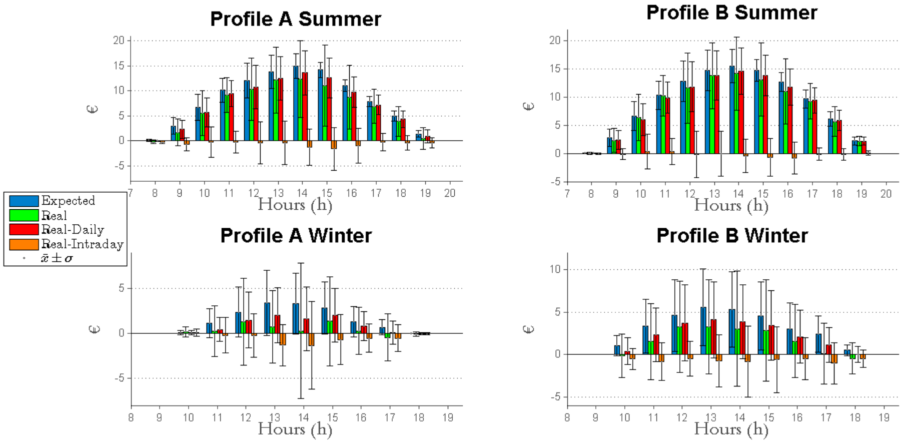

Figure 5.12: Representation of the average market result composition by source.

In Figure 5.12 it can be seen the average composition of the market result per period, considering both consumption profiles and different sets of data. The first major conclusion to extract is that the expected market revenue is always higher than the actual outcome obtained, which is in line with the previous points of the analysis of results. It can also be observed that the participation in the intraday sessions has invariably negative outcomes, which comes as a necessary effect of the previous conclusion. This means that the trading in this secondary market mainly occurs to acquire the deficit of generation output, relative to the contracted amount. Again, and being a decomposition of the market results displayed in the previous section, it is noted the large fluctuation in standard deviations, when comparing to the values itself. More detailed results can be seen in Table A.13 and Table A.14.

5.3.4 Model application results

Results for the application of the model in comparison to the current regime of remuneration of private PV generation can be seen in the graph below.

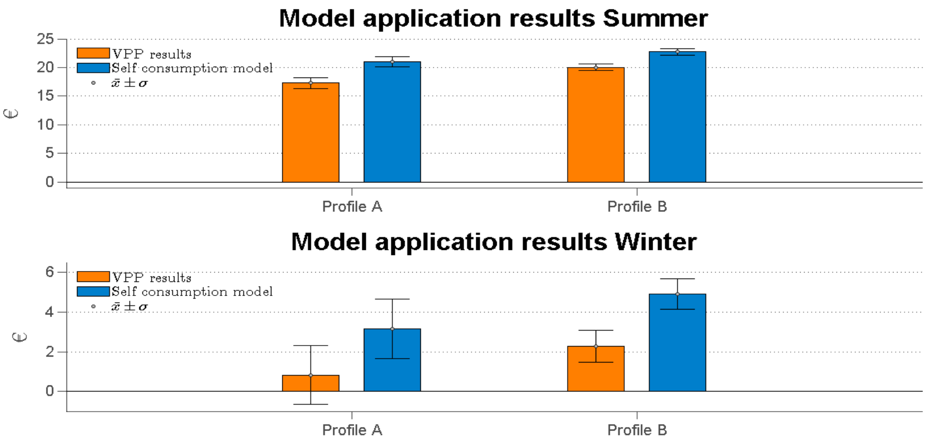

Figure 5.13: Average revenue per client per day considering the two distinct remuneration regimes.

In Figure 5.13 is shown the average market result per client per day in the four distinct sets of data, considering both remuneration systems. It is clear that the self-consumption model would provide higher revenues for any client, whether having a consumption profile of type A or B, and in both periods. A contrary result to what was theoretically expected, since the pricing model practiced in the self-consumption regime takes the average day-ahead price of a given month with a 10% discount to remunerate electrical energy produced. On the other hand, the model implemented in the simulator executes the trade of the available energy of each period at the price practiced at said hour. This remuneration system avoids the effect of averaging the price with the inclusion of lower priced periods, such as those during night time in which there is no generation output.

Average day-ahead price comparison	Self-consumption			VPP model	
	September	August	February	Summer	Winter
€/MWh	53,02	44,92	38,31	53,89 ± 6,50	46,21 ± 12,68

Table 5.5: Average day-ahead prices comparison between the two remuneration models

In Table 5.6 can be observed the comparison of the day-ahead prices considered in both remuneration models, confirming that in the model developed in this project the prices at which energy is traded are higher. However, since simulator results include the process of forecasting electricity production, resorting to the intraday market to make up for shortages, the average revenue per client turns out to be lower than it would be considering the self-consumption regime. The model's tendency to overestimate available energy overcomes the theoretical advantages of the remuneration system, by reducing revenues with the additional costs of buying the deficits in the intraday sessions. Results are synthetized in Table 5.6.

Model aplication results	Summer		Winter	
	Profile A	Profile B	Profile A	Profile B
VPP results (€)	17,28 ± 0,94	20,95 ± 0,89	0,82 ± 1,48	3,14 ± 1,50
Self consumption model (€)	20,01 ± 0,56	22,74 ± 0,55	2,27 ± 0,79	4,92 ± 0,77

Table 5.6: Average revenue per client considering the two distinct remuneration regimes.

6 Conclusion and future work

It was intended with the development of this project the implementation and assessment of an electricity market simulator that comprised the current technical and regulatory framework in Portugal and in the MIBEL in general. Through this simulator it was expected to be obtained a clear view on the ideal conditions and settings under which a VPP would be more successful in the participation in the wholesale market. Finally, it was projected an evaluation on the viability of the use of this simulator as an aiding tool for VPP operators.

After analyzing the results posted and discussed in the precedent chapter, it is largely accepted that the objectives of this study were effectively met. With the simulation model developed under the parameters and characteristics described in chapter 4, it was possible to conclude on the proper conditions on which the VPP would present better outcome results. More specifically, it is recognized, as previously expected that the VPP operation in the market presents better results if the set of clients is composed by individual producers with consumption patterns of profile B. Numerical results support this conclusion with an average market result per day of 99,73 € and 14,94 € for profile B clients in the summer and winter respectively against 82,26 € and 3,89 € for profile A clients, for the correspondent periods. From the same results it is also clear that a VPP would present significantly greater revenues from its operation during periods with longer solar exposition times and higher solar irradiance values, correspondent in this project to the set of days relative to the summer period.

Regarding the simulator itself as a modelling tool for the operation of a VPP, the set of results confirm the validity of the implemented model, since the expected outcomes for the different initial conditions are generally and successfully emulated. However, it was perceived in the estimation process of the simulator a general tendency for overestimating the amount of available electricity provided by the set of clients, affecting the ability to accurately predict the market results for the VPP as a whole. This general tendency may be caused by uncertainties in the input data of the model as it was noted in the error composition analysis, where it was observed the alternate behavior of the generation and consumption average error.

Against what was expected, the application of the model regarding the comparison of the remuneration system with the alternative Self-consumption regime determined that the average remuneration per day per client would be lower if they were included in the VPP system. This is mainly due to the overestimation of available energy, forcing the purchase of the missing electricity in the intraday sessions and lowering the predicted revenues. In this case, when alternative systems might present such close results, the VPP model projected in this thesis may fall short when estimating the most viable option for individual producers to sell their available energy.

When most of the feed-in-tariffs benefiting clients reach the end of their contracts or their tariffs are comparable to the wholesale prices, there will be space in the market for new remuneration models. However, at the light of these results, it is perceived a difficult path for the effective introduction of VPP's in the wholesale market for electricity, in what respects the sale of domestic production in the wholesale market. With the current legislation, as results from the alternative remuneration system showed, there is no financial advantage in integrating a VPP system with the intent of injecting generation in the grid at day-ahead prices. In this perspective, given the results for the remuneration comparison analysis and, considering that no operational costs were considered for the projected model, which, if taken into account, should lower the revenue per client, it is expected that in the future, the Self-consumption regime should absorb most VPP potential clients. However, if the VPP project should consider demand control functionality, with the possibility of shifting the bulk of the consumption to the periods when PV generation is at its peak, the model should present better financial viability. The benefits arising from reducing consumption are greater than those based in the sale of generation in the wholesale market, since the savings correspond to energy not bought at retail price, which is always higher than the wholesale price.

The viability of the VPP model in a technical and regulatory framework as the Portuguese grid, seems to be available only to projects where the VPP is able to ensure a technical role with control over generation and demand.

As limitations shortening the scope and application of the present study it should be noted the following as the most relevant:

- Absence of actual results of generation for the sites modeled in the simulator. This data would be of great interest to validate the effectiveness of the production module.
- Absence of a price penalty model for the contracted energy predicted by the VPP. This would have the implemented model closer to the real electricity market operation.
- Lack of time synchronism between consumption data and generation data. The set of consumption data is from 2012, while the generation estimations are from 2014 and 2015, which may induce further fluctuations in the results.
- Retroaction of the estimation model that operates using forecasts from the prior days to predict electricity generation for a day in the past. An estimation of future production values was not implemented.

In order to improve the model results and gain a better understanding on the simulation and viability of the VPP operation in the market, the following aspects should be considered in future studies:

- Weather forecasts and real production data from additional sites. This is an important feature that will allow corroboration of the model for most general conditions, both through the validation of the production module as well as the geographical coverage for application of the simulator.

- Simulation runs and analysis of longer time periods, with a minimum of one year, would allow improvements in the statistical treatment and hence the in the solidity of numerical results, enabling a better and more complete understanding of the behavior of a VPP in larger intervals of time, closer to the interest of the individual producer.

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Appendix

Simulation results

General results

	Generation Data (kWh)							
	Summer				Winter			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	15,77 ±10,02	7,55	16,21	23,38	-	-	-	-
9	74,97 ± 33,45	64,46	87,90	99,18	3,96 ± 4,94	0,01	2,21	5,27
10	148,41 ± 45,27	152,09	162,75	172,46	36,70 ± 33,73	3,08	24,19	70,42
11	210,64 ± 42,86	212,66	223,53	233,20	75,88 ± 60,59	15,07	54,92	139,31
12	243,13 ± 67,31	258,54	267,89	277,45	119,49 ± 78,42	28,99	145,40	193,64
13	273,99 ± 62,28	285,62	292,56	302,85	136,94 ± 82,86	55,63	150,09	223,11
14	282,81 ± 64,41	294,07	300,02	309,50	145,11 ± 84,11	57,69	150,61	230,30
15	274,34 ± 55,29	281,01	287,61	297,34	131,29 ± 84,33	36,11	144,34	215,42
16	243,70 ± 53,18	248,95	256,98	266,96	96,76 ± 74,96	21,80	64,97	175,65
17	201,07 ± 34,85	199,38	208,44	217,90	60,92 ± 54,39	7,88	36,58	117,89
18	135,99 ± 32,17	135,42	143,50	153,66	27,72 ± 25,13	1,28	34,73	50,29
19	67,43 ± 18,06	62,50	70,90	79,47	0,22 ± 0,53	0,00	0,00	0,14
20	6,40 ± 4,82	2,12	5,83	10,57	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.1: Generation results for both periods, considering average values and 25th, 50th and 75th percentiles.

Consumption Data (kWh) Summer								
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	58,30 ± 23,74	40,02	50,86	68,39	42,59 ± 6,01	38,28	41,10	45,83
2	52,33 ± 20,34	37,47	48,65	65,11	31,37 ± 5,82	26,44	31,96	34,48
3	43,67 ± 22,62	30,99	35,27	48,48	27,47 ± 6,10	23,38	25,75	30,79
4	34,57 ± 11,51	27,97	29,48	37,61	26,89 ± 5,79	22,82	24,55	30,02
5	29,22 ± 4,47	25,92	27,62	31,18	25,17 ± 5,06	21,92	22,89	28,55
6	28,17 ± 2,91	26,03	27,57	29,32	24,86 ± 5,19	20,76	22,90	28,57
7	27,68 ± 2,54	25,83	27,23	28,92	22,12 ± 2,44	20,23	21,82	23,95
8	26,94 ± 2,00	25,61	26,09	27,91	23,52 ± 2,19	21,81	23,34	24,81
9	29,28 ± 6,63	25,63	26,82	29,96	23,74 ± 2,70	21,88	23,73	24,98
10	33,85 ± 7,34	27,90	33,32	37,64	24,96 ± 5,29	20,21	23,77	27,51
11	36,96 ± 9,56	30,41	33,66	42,65	24,95 ± 4,19	21,71	24,15	26,34
12	42,30 ± 10,83	35,02	39,73	45,93	25,74 ± 5,30	22,07	24,11	26,30
13	45,95 ± 15,24	32,98	42,50	61,70	25,20 ± 4,80	22,39	23,68	27,96
14	47,90 ± 16,78	34,38	43,77	54,44	27,18 ± 7,58	22,35	24,80	28,82
15	51,30 ± 18,12	37,45	48,54	55,46	28,20 ± 7,68	22,38	24,73	31,93
16	55,85 ± 25,38	33,48	47,78	65,36	25,89 ± 7,39	21,61	22,20	26,22
17	57,17 ± 19,75	41,31	55,84	71,18	23,79 ± 4,26	21,09	22,67	25,32
18	48,62 ± 13,80	36,60	45,84	59,65	23,93 ± 3,29	21,49	22,83	26,91
19	47,89 ± 17,16	36,73	48,28	52,77	25,45 ± 3,17	23,47	25,95	26,55
20	39,53 ± 10,30	30,80	39,44	42,37	31,57 ± 7,13	25,69	30,19	35,52
21	42,71 ± 14,41	34,70	39,80	45,48	35,55 ± 8,45	28,42	32,63	40,60
22	53,17 ± 21,89	40,05	44,52	64,61	41,29 ± 12,18	31,93	37,85	49,01
23	65,69 ± 25,60	46,24	56,57	78,71	42,27 ± 7,14	36,16	42,28	47,60
24	58,96 ± 27,60	39,55	46,95	77,36	43,24 ± 5,20	40,46	43,11	46,30

Table A.2: Summer period consumption results, considering average values and 25th, 50th and 75th percentiles.

Consumption Data (kWh) Winter								
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	75,56 ± 22,82	54,48	78,00	85,51	95,90 ± 14,22	88,88	95,06	104,34
2	59,72 ± 21,49	44,98	56,45	80,08	67,76 ± 15,52	55,38	64,39	76,66
3	38,72 ± 10,96	31,75	37,16	45,39	75,77 ± 15,76	61,33	76,39	84,97
4	35,45 ± 12,85	24,84	34,15	39,46	79,02 ± 16,46	64,17	77,11	94,38
5	32,97 ± 10,33	24,18	32,15	38,34	58,66 ± 16,05	42,84	58,10	73,90
6	29,33 ± 7,47	22,32	30,95	34,45	49,63 ± 14,95	40,14	45,77	53,45
7	35,24 ± 12,78	25,73	33,33	39,72	65,61 ± 17,55	55,76	58,61	69,25
8	44,68 ± 14,32	33,63	42,11	55,33	76,75 ± 17,73	68,18	71,74	79,88
9	73,89 ± 30,91	49,93	69,66	98,09	53,35 ± 10,15	46,49	52,94	61,63
10	66,52 ± 26,94	46,05	59,92	86,72	32,63 ± 15,20	20,68	26,23	41,56
11	79,70 ± 30,14	50,54	79,65	100,36	30,48 ± 18,82	19,02	20,31	35,92
12	102,23 ± 42,84	63,14	102,89	137,84	31,41 ± 20,05	18,71	20,72	43,46
13	95,71 ± 26,73	73,47	94,99	115,38	36,07 ± 25,38	19,61	23,26	47,72
14	89,62 ± 44,45	53,16	87,94	108,42	34,60 ± 21,41	19,25	21,62	46,85
15	78,27 ± 28,06	57,63	84,37	90,24	36,69 ± 21,92	21,33	25,09	47,56
16	90,33 ± 33,21	63,56	91,77	115,57	32,22 ± 21,69	18,91	21,11	46,18
17	70,36 ± 24,93	49,40	63,83	85,45	33,16 ± 19,33	19,42	26,30	37,84
18	72,28 ± 24,57	52,58	66,28	95,23	40,73 ± 21,27	28,67	33,42	46,02
19	81,65 ± 24,19	66,27	85,21	97,55	53,95 ± 19,47	41,19	47,40	63,74
20	75,20 ± 30,79	48,45	65,19	88,72	75,47 ± 22,31	61,63	69,25	88,38
21	93,54 ± 34,13	68,24	89,79	105,94	82,11 ± 22,13	65,13	81,47	101,70
22	106,79 ± 44,47	77,06	97,86	130,08	80,65 ± 19,80	65,65	81,04	98,54
23	93,92 ± 34,60	67,04	95,56	113,07	98,86 ± 16,11	85,40	101,85	108,84
24	90,76 ± 29,53	71,21	81,70	114,34	131,60 ± 16,45	123,30	129,60	143,00

Table A.3: Winter period consumption results, considering average values and 25th, 50th and 75th percentiles.

Day-Ahead Market Prices (€/MWh)								
	Summer				Winter			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	52,15 ± 6,32	46,61	50,24	56,46	41,62 ± 11,99	32,18	42,47	50,10
2	47,78 ± 5,53	44,73	45,00	50,00	37,38 ± 11,22	28,46	37,10	47,12
3	45,53 ± 4,87	43,29	44,54	45,93	33,02 ± 12,33	24,58	35,01	43,97
4	45,70 ± 4,61	43,33	44,64	45,95	31,39 ± 11,63	23,15	33,18	41,58
5	44,85 ± 5,12	42,81	44,54	45,49	30,53 ± 11,73	21,53	31,43	41,04
6	45,64 ± 5,12	43,67	44,58	46,20	32,00 ± 11,54	24,90	32,85	41,94
7	49,14 ± 6,67	44,52	45,40	55,14	36,52 ± 11,82	29,67	38,40	45,85
8	52,83 ± 7,66	44,92	52,78	58,17	47,88 ± 14,16	42,22	52,00	56,88
9	55,03 ± 7,75	47,74	56,50	60,50	49,39 ± 14,04	41,85	53,10	57,48
10	57,70 ± 7,72	53,80	60,00	62,76	54,29 ± 14,06	47,75	57,25	61,17
11	58,01 ± 7,69	53,15	61,00	62,88	55,98 ± 13,34	48,57	58,49	62,63
12	58,71 ± 7,26	55,25	60,01	63,58	54,19 ± 13,16	46,55	55,19	60,82
13	59,36 ± 7,17	54,87	60,49	64,14	51,67 ± 14,16	43,95	54,35	60,06
14	59,43 ± 7,22	54,71	61,00	64,21	49,40 ± 13,42	41,97	51,38	58,30
15	57,51 ± 6,64	54,26	58,46	61,74	44,83 ± 14,15	36,73	43,89	54,28
16	55,01 ± 6,76	50,73	55,96	59,78	42,86 ± 15,57	32,82	42,59	52,07
17	53,88 ± 7,32	48,56	55,12	60,25	43,39 ± 16,56	32,18	43,89	53,27
18	53,85 ± 7,67	47,80	54,87	60,51	45,93 ± 15,88	35,12	49,64	55,62
19	53,91 ± 7,39	47,52	54,87	59,35	51,57 ± 12,64	41,97	52,60	61,26
20	54,56 ± 7,04	48,44	54,66	60,06	60,35 ± 11,87	53,14	61,01	70,27
21	57,41 ± 6,35	54,10	55,12	64,08	60,48 ± 10,31	54,59	60,19	66,42
22	62,12 ± 4,86	57,78	61,80	66,01	55,87 ± 8,97	50,59	54,49	60,97
23	59,63 ± 3,69	56,48	58,80	61,63	51,78 ± 9,22	45,17	52,03	56,43
24	55,39 ± 4,54	52,37	54,96	58,33	46,84 ± 10,62	39,10	46,30	53,86

Table A.4: Day-ahead market prices for both periods, considering average values and 25th, 50th and 75th percentiles.

Market Results

	Energy Balance Data (kWh)							
	Summer							
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-0,25 ± 2,34	-0,16	0,00	0,00	0,87 ± 2,49	0,00	0,00	0,00
9	46,26 ± 33,84	0,00	60,63	72,35	50,14 ± 32,12	1,54	65,98	74,43
10	115,69 ± 44,88	112,72	133,17	137,50	124,03 ± 42,79	126,60	138,30	142,94
11	173,68 ± 44,99	176,08	189,12	197,52	185,68 ± 42,75	187,11	197,90	209,29
12	200,83 ± 67,10	211,09	226,94	233,47	217,39 ± 66,84	235,68	241,74	250,87
13	228,05 ± 68,46	225,23	254,24	262,46	248,79 ± 61,70	261,06	267,53	275,84
14	234,91 ± 73,25	237,27	260,05	271,01	255,63 ± 64,66	268,45	273,31	281,65
15	223,04 ± 68,38	227,91	241,75	258,55	246,15 ± 56,16	252,85	260,51	268,88
16	187,84 ± 61,43	176,39	210,73	226,18	217,80 ± 52,45	224,74	228,76	239,97
17	143,90 ± 42,37	128,43	155,28	168,18	177,28 ± 34,86	176,55	181,08	193,15
18	87,37 ± 37,00	75,20	98,86	109,09	112,06 ± 31,60	113,33	119,52	126,94
19	21,34 ± 25,03	8,46	28,28	40,89	43,19 ± 13,32	39,59	43,07	53,39
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.5: Summer period balance results, considering average values and 25th, 50th and 75th percentiles.

	Energy Balance Data (kWh)							
	Winter							
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	2,93 ± 9,15	0,00	0,00	0,00	8,55 ± 31,63	0,00	0,00	43,09
11	17,50 ± 36,41	0,00	0,00	40,56	44,89 ± 60,21	0,00	0,00	113,82
12	37,75 ± 67,57	0,00	0,00	96,48	77,06 ± 84,03	0,00	24,39	165,31
13	43,55 ± 61,97	0,00	0,00	117,67	91,48 ± 88,35	0,00	59,53	191,03
14	48,69 ± 85,47	0,00	0,00	128,76	92,14 ± 91,55	0,00	111,79	179,76
15	51,35 ± 78,08	0,00	0,00	129,31	86,96 ± 92,09	0,00	71,80	190,67
16	21,62 ± 45,59	0,00	0,00	59,91	59,32 ± 76,05	0,00	10,48	147,17
17	7,01 ± 37,14	0,00	0,00	33,34	33,56 ± 47,52	0,00	20,97	86,94
18	-1,47 ± 6,59	0,00	0,00	0,00	0,87 ± 20,23	-0,87	0,00	5,95
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.6: Winter period balance results, considering average values and 25th, 50th and 75th percentiles.

Market Results Data (€) Summer								
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-0,22 ± 0,37	-0,37	0,00	0,00	0,01 ± 0,15	0,00	0,00	0,00
9	1,71 ± 2,64	0,00	2,74	3,36	2,31 ± 2,16	0,00	3,33	3,88
10	5,55 ± 4,43	6,38	6,91	7,31	6,37 ± 4,07	6,75	7,82	8,11
11	9,17 ± 3,54	8,81	10,02	11,19	10,24 ± 3,55	9,39	11,83	12,56
12	10,37 ± 6,25	10,81	12,75	14,23	11,62 ± 6,24	10,74	14,23	15,37
13	12,16 ± 6,58	12,08	14,59	15,80	13,79 ± 5,88	12,54	15,47	17,20
14	12,37 ± 7,68	12,66	15,23	16,31	14,19 ± 6,49	13,12	16,61	17,58
15	11,03 ± 8,12	12,03	13,11	14,81	13,11 ± 6,52	12,57	15,23	16,12
16	8,80 ± 6,37	8,50	10,58	12,81	11,00 ± 5,82	10,13	13,14	13,89
17	6,93 ± 3,47	5,87	8,09	8,75	9,24 ± 3,12	8,52	10,52	10,88
18	3,92 ± 3,02	3,28	4,78	5,53	5,66 ± 2,60	5,39	6,52	7,05
19	0,48 ± 2,22	-0,07	1,17	2,04	2,20 ± 0,80	1,99	2,37	2,67
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.7: Summer period market results, considering average values and 25th, 50th and 75th percentiles.

Market Results Data (€) Winter								
	Profile A				Profile B			
Hour	Average	Per. 25	Per. 50	Per. 75	Average	Per. 25	Per. 50	Per. 75
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	0,16 ± 0,54	0,00	0,00	0,00	-0,14 ± 2,55	-0,49	0,00	2,20
11	0,26 ± 2,82	0,00	0,00	1,07	1,51 ± 4,45	0,00	0,00	5,81
12	1,29 ± 4,83	0,00	0,00	4,73	3,25 ± 5,38	0,00	1,77	8,55
13	0,73 ± 4,02	0,00	0,00	3,32	3,29 ± 5,54	-0,38	1,43	9,05
14	0,29 ± 7,54	0,00	0,00	5,41	3,03 ± 6,76	0,00	2,71	7,81
15	1,35 ± 4,93	0,00	0,00	5,47	2,81 ± 5,99	0,00	2,85	7,79
16	0,29 ± 2,62	0,00	0,00	1,13	1,57 ± 4,30	-0,44	0,00	4,92
17	-0,44 ± 2,64	-0,12	0,00	0,81	0,09 ± 3,61	-2,73	0,00	2,60
18	-0,06 ± 0,25	0,00	0,00	0,00	-0,48 ± 1,85	-0,39	0,00	0,10
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.8: Winter period market results, considering average values and 25th, 50th and 75th percentiles.

Error tendency and composition results

Accumulated available energy error (kWh)				
	Summer		Winter	
Hour	Profile A	Profile B	Profile A	Profile B
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	-74,20	-0,75	-	-
9	-200,01	-21,63	-	-
10	-54,74	145,04	27,60	-212,64
11	-74,56	120,39	-56,36	-303,99
12	-145,82	-59,83	-100,92	-155,13
13	-109,97	-5,04	-463,98	-333,71
14	-370,31	-112,59	-436,14	-343,00
15	-506,27	-206,70	-313,96	-313,50
16	-309,04	-260,01	-268,26	-274,40
17	-87,05	-53,40	-222,37	-448,44
18	-129,52	-51,96	-35,33	-208,45
19	-139,38	24,38	-	-
20	-	-	-	-
21	-	-	-	-
22	-	-	-	-
23	-	-	-	-
24	-	-	-	-

Table A.9: Cumulative available error results for the different sets of conditions.

Accumulated market result error (€)				
	Summer		Winter	
Hour	Profile A	Profile B	Profile A	Profile B
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	-7,99	-0,59	-	-
9	-26,86	-9,04	-	-
10	-33,77	-5,53	1,89	-24,93
11	-21,90	-1,59	-18,30	-38,02
12	-6,28	-25,51	-22,84	-28,40
13	5,32	-19,85	-56,69	-47,62
14	-34,98	-27,73	-63,76	-47,45
15	-28,91	-34,34	-31,11	-36,20
16	-19,49	-35,06	-21,59	-30,61
17	-4,87	-9,31	-23,77	-40,68
18	-11,41	-10,32	-1,25	-20,96
19	-9,34	-0,98	-	-
20	-	-	-	-
21	-	-	-	-
22	-	-	-	-
23	-	-	-	-
24	-	-	-	-

Table A.10: Cumulative market errors results for the different sets of conditions.

Average available energy error composition (kWh)						
Summer						
	Profile A			Profile B		
Hour	Balance	Generation	Consumption	Balance	Generation	Consumption
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	-3,53 ± 4,97	0,85 ± ,99	8,03 ± 2,48	-0,04 ± 1,99	0,85 ± 4,99	-3,30 ± 3,43
9	-9,52 ± 19,16	1,78 ± 21,39	10,23 ± 6,80	-1,03 ± 15,76	1,78 ± 21,39	-1,09 ± 2,97
10	-2,61 ± 45,73	6,62 ± 46,10	10,02 ± 6,01	6,91 ± 46,96	6,62 ± 46,10	-0,33 ± 5,47
11	-3,55 ± 32,92	4,51 ± 33,68	8,06 ± 8,68	5,73 ± 34,48	4,51 ± 33,68	-1,22 ± 3,15
12	-6,94 ± 63,64	-2,63 ± 62,95	4,32 ± 10,90	-2,85 ± 62,21	-2,63 ± 62,95	0,22 ± 3,16
13	-5,24 ± 64,72	-2,11 ± 58,98	3,12 ± 13,34	-0,24 ± 59,74	-2,11 ± 58,98	-1,87 ± 5,50
14	-17,63 ± 51,11	-9,78 ± 40,79	7,85 ± 15,37	-5,36 ± 42,47	-9,78 ± 40,79	-4,42 ± 9,89
15	-24,11 ±63,71	-14,37 ± 49,67	9,74 ± 19,27	-9,84 ± 49,51	-14,37 ± 49,67	-4,53 ± 9,41
16	-14,72 ± 54,20	-13,26 ± 45,12	1,46 ± 23,38	-12,38 ± 45,23	-13,26 ± 45,12	-0,88 ± 8,12
17	-4,15 ± 28,81	-4,59 ± 17,45	-0,45 ± 19,62	-2,54 ± 17,95	-4,59 ± 17,45	-2,05 ± 4,91
18	-6,1674 ± 22,37	-5,04 ± 16,11	1,13 ± 12,06	-2,47 ± 15,69	-5,04 ± 16,11	-2,56 ± 3,86
19	-6,64 ± 15,81	-1,47 ± 4,32	6,16 ± 14,41	1,16 ± 6,39	-1,47 ± 4,32	-2,41 ± 5,09
20	-	-0,03 ± 0,70	6,70 ± 8,93	-	-0,03 ± 0,70	4,67 ± 6,39
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-

Table A.11: Average balance error composition results for the summer period.

Average available energy error composition (kWh)						
Winter						
	Profile A			Profile B		
Hour	Balance	Generation	Consumption	Balance	Generation	Consumption
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	-	1,31 ± 4,34	3,95 ± 34,47	-	1,31 ± 4,34	24,38 ± 9,99
10	1,31 ± 5,89	1,70 ± 28,93	-21,12 ± 31,44	-10,13 ± 23,81	1,70 ± 28,93	4,18 ± 15,34
11	-2,68 ± 33,52	-2,73 ± 41,75	-16,69 ± 36,11	-14,48 ± 37,90	-2,73 ± 41,75	3,42 ± 20,40
12	-4,81 ± 45,45	10,67 ± 51,44	0,11 ± 42,07	-7,39 ± 42,76	10,67 ± 51,44	2,04 ± 25,01
13	-22,09 ± 47,03	2,13 ± 62,61	5,48 ± 31,07	-15,89 ± 58,46	2,13 ± 62,61	6,94 ± 27,01
14	-20,77 ± 86,16	9,80 ± 86,15	4,78 ± 44,89	-16,33 ± 74,02	9,80 ± 86,15	5,99 ± 25,74
15	-14,95 ± 62,57	1,95 ± 71,12	-2,53 ± 28,99	-14,93 ± 70,12	1,95 ± 71,12	6,41 ± 25,04
16	-12,77 ± 41,69	-1,91 ± 54,34	-6,76 ± 36,16	-13,07 ± 53,47	-1,91 ± 54,34	2,62 ± 22,59
17	-10,59 ± 32,04	-18,04 ± 42,75	-16,81 ± 28,14	-21,35 ± 47,93	-18,04 ± 42,75	2,98 ± 25,00
18	-1,68 ± 7,52	-3,15 ± 14,94	-8,68 ± 25,33	-9,93 ± 18,57	-3,15 ± 14,94	8,33 ± 23,79
19	-	-0,04 ± 0,11	2,05 ± 28,66	-	-0,04 ± 0,11	15,02 ± 19,79
20	-	-	-	-	-	-
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-

Table A.12: Average balance error composition results for the winter period.

Market results composition (€)								
Summer								
	Profile A				Profile B			
Hour	Expected	Real	Real - Daily	Real - Intraday	Expected	Real	Real - Daily	Real - Intraday
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	0,16 ± 0,22	-0,22 ± 0,37	-0,02 ± 0,11	-0,20 ± 0,29	0,04 ± 0,09	0,01 ± 0,154	0,02 ± 0,06	-0,01 ± 0,11
9	2,99 ± 1,64	1,71 ± 2,64	2,34 ± 1,82	-0,6299 ± 1,28	2,74 ± 1,54	2,31 ± 2,16	2,44 ± 1,67	-0,13 ± 0,96
10	6,67 ± 2,62	5,55 ± 4,43	5,76 ± 2,90	-0,2102 ± 3,07	6,63 ± 2,63	6,37 ± 4,07	6,01 ± 2,85	0,36 ± 3,12
11	10,13 ± 2,37	9,17 ± 3,53	9,42 ± 2,62	-0,25 ± 2,20	10,31 ± 2,54	10,24 ± 3,55	9,90 ± 2,74	0,34 ± 2,31
12	12,09 ± 3,47	10,37 ± 6,25	10,82 ± 4,32	-0,45 ± 4,21	12,84 ± 3,61	11,62 ± 6,24	11,81 ± 4,45	-0,19 ± 4,13
13	13,76 ± 3,33	12,16 ± 6,58	12,53 ± 4,39	-0,37 ± 4,36	14,73 ± 3,56	13,79 ± 5,88	13,82 ± 4,34	-0,03 ± 4,03
14	14,95 ± 2,43	12,37 ± 7,68	13,61 ± 4,37	-1,24 ± 3,64	15,51 ± 2,91	14,19 ± 6,49	14,65 ± 4,13	-0,45 ± 2,97
15	14,19 ± 1,53	11,03 ± 8,12	12,62 ± 3,99	-1,59 ± 4,28	14,74 ± 1,98	13,11 ± 6,52	13,82 ± 3,55	-0,72 ± 3,31
16	11,09 ± 1,19	8,80 ± 6,37	9,77 ± 3,10	-0,97 ± 3,42	12,67 ± 1,72	11,00 ± 5,82	11,82 ± 3,55	-0,82 ± 2,87
17	7,90 ± 1,00	6,93 ± 3,47	7,21 ± 1,91	-0,27 ± 1,73	9,69 ± 1,62	9,24 ± 3,12	9,42 ± 2,22	-0,18 ± 1,09
18	4,96 ± 0,98	3,92 ± 3,02	4,34 ± 1,71	-0,43 ± 1,47	6,15 ± 1,3	5,66 ± 2,60	5,85 ± 1,75	-0,19 ± 1,05
19	1,42 ± 0,62	0,48 ± 2,22	0,90 ± 1,29	-0,42 ± 1,00	2,25 ± 0,7	2,20 ± 0,80	2,16 ± 0,72	0,04 ± 0,37
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.13: Average market result composition for the summer period.

Market results composition (€)								
Winter								
	Profile A				Profile B			
Hour	Expected	Real	Real - Daily	Real - Intraday	Expected	Real	Real - Daily	Real - Intraday
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	0,07 ± 0,26	0,16 ± 0,54	0,07 ± 0,26	0,09 ± 0,40	1,05 ± 1,21	-0,14 ± 2,55	0,39 ± 1,57	-0,53 ± 1,22
11	1,13 ± 1,60	0,26 ± 2,82	0,46 ± 1,32	-0,20 ± 1,99	3,32 ± 3,18	1,51 ± 4,45	2,33 ± 3,16	-0,82 ± 2,20
12	2,38 ± 2,79	1,29 ± 4,83	1,49 ± 3,13	-0,20 ± 2,42	4,61 ± 4,23	3,25 ± 5,38	3,72 ± 4,44	-0,47 ± 2,03
13	3,43 ± 3,63	0,73 ± 4,02	2,03 ± 3,06	-1,30 ± 2,30	5,56 ± 4,53	3,29 ± 5,54	4,07 ± 4,49	-0,78 ± 3,07
14	3,33 ± 3,41	0,29 ± 7,54	1,63 ± 3,57	-1,34 ± 4,88	5,29 ± 4,43	3,03 ± 6,76	3,85 ± 4,38	-0,82 ± 4,16
15	2,83 ± 2,87	1,35 ± 4,93	2,04 ± 2,98	-0,69 ± 2,77	4,54 ± 4,01	2,81 ± 5,99	3,43 ± 4,10	-0,62 ± 3,86
16	1,32 ± 1,70	0,29 ± 2,62	0,81 ± 1,59	-0,51 ± 1,58	3,03 ± 3,05	1,57 ± 4,30	2,09 ± 3,13	-0,52 ± 2,49
17	0,70 ± 0,83	-0,44 ± 2,64	0,11 ± 1,27	-0,54 ± 1,49	2,37 ± 2,14	0,09 ± 3,61	1,13 ± 2,05	-1,05 ± 2,46
18	0,00 ± 0,02	-0,06 ± 0,25	-0,03 ± 0,12	-0,03 ± 0,13	0,52 ± 0,65	-0,48 ± 1,85	0,01 ± 0,95	-0,49 ± 0,99
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-

Table A.14: Average market result composition for the winter period.