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The potential impacts of Electric Vehicles on the Energy Production Mix and Market Operation: the Portuguese case.

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THE POTENTIAL IMPACTS OF ELECTRIC VEHICLES INTO THE PRODUCTION ENERGY MIX AND MARKET OPERATION: THE PORTUGUESE CASE

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Abstract

The milestones established in the Paris Agreement stated the utmost necessity to fight climate change, through a sustainable development path. Electric vehicles can help cutting down greenhouse gases emissions since these vehicles don't directly rely on fossil fuels. However, higher penetration rates of electric vehicles has its downsizes such as increase electricity demand. To address this issue, more energy must be supplied (preferentially renewable electricity) in order to integrate electric vehicle fleets into national grids and at the same time follow what was defined by the Paris Agreement.

This work tried to understand how would the market respond to an increased demand for electricity in peak hours and how much would the prices (market clearing prices) increase, if an electric vehicle fleet was connected to the grid. Historic data from 2016 and 2017 was used to compare the historic market clearing prices with the ones obtained by the simulation model used in this work. The obtained results showed that the electric grid is not yet prepared to embrace large electric fleets and when the grid managed to supply enough energy demanded, prices rose substantially for medium to big sized fleets.

In conclusion, electric vehicle integration into the Portuguese grid will only be plausible if the electricity wholesale market operation is prepared to answer to demand increase by supplying enough energy, especially in critic moments of the day, such as peak hours. The electricity generation mix could also play an important role regarding peak price shaping. Integrating more renewable electricity, namely wind energy, into the whole sale market and thus managing price increase in peak hours.

Key words: Electric vehicles, market clearing price, electricity wholesale market, market operation, energy mix.

Resumo

As metas estabelecidas pelo Acordo de Paris deixaram claro a necessidade de combater as alterações climáticas e o aquecimento global. Para isso, várias medidas devem ser adoptadas para reduzir as emissões de gases com efeito de estufa. Os veículos elétricos podem ajudar na redução destes gases ums vez que não dependem de combustíveis fósseis para se movimentar. Contudo, uma maior penetração destes veículos nos parques automóveis tem de ser bem estudada, uma vez que os veículos elétricos representam uma carga adicional para as redes elétricas, o que se traduz num aumento da procura de electricidade. Para satisfazer este aumento de procura, deve-se responder com mais oferta de energia preferencialmente renovável, para que seja possível integrar estes veículos de forma sustentável e assim respeitar o Acordo de Paris.

Este trabalho tem como objectivo perceber quais teriam sido as consequencias económicas (em termos de preço do mercado grossista de electricidade) de integrar frotas de veículos elétricos em Portugal. Para tal, foi avaliado como variariam os preços (*market clearing prices*) em função de três frotas diferentes, em termos de números de veículos, no sistema elétrico português, recorrendo a dados históricos de 2016 e 2017. Os resultados obtidos demonstram claramente que a rede elétrica não está, neste momento, preparada para aguentar grandes frotas de veículos elétricos. Não obstante, é esperado que os preços médios de electricidade subam nas horas em que os veículos elétricos estejam a carregar.

Desta forma, concluiu-se que a integração de veículos elétricos a médio e longo prazo em Portugal dependerá da forma de operação do mercado de electricidade, no sentido dos produtores e outras partes interessadas estarem preparados para as acrescidas necessidades dos veículos eléctricos. O mix de produção de electricidade também é importante para os impactes dos carros elétricos, nomeadamente nos carregamentos em horas de pico. Nestes casos, deve-se tentar usufruir da mair penetração de renováveis, principalmente éolica, para evitar um aumento exagerado dos preços.

Palavras chave: veículos eléctricos, market clearing prices, mercado grossista de electricidade, operação de mercado, mix energético.

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List of Acronyms

2DS . . . . IEA Two-degree Scenario
AC . . . . Altering Current
ACAP . . . . Associação Automóvel de Portugal
AMI . . . . Advanced Metering Infrastructure
B2DS . . . . IEA Beyond Two-degree Scenario
BEVs . . . . Battery Electric Vehicles
CC . . . . Constant Current
CP . . . . Constant Power
CV . . . . Constant Voltage
DC . . . . Direct Current
EDP . . . . Energias de Portugal
EPXs . . . . European Power Exchanges
EUPHEMIA. . . . . . Pan-European Hybrid Electricity Market Integration Algorithm
EVs . . . . Electric Vehicles
EVI . . . . Electric Vehicle Initiative
EVSE . . . . Electric Vehicles Associated Equipments
GHG . . . . Greenhouse gases
HAN . . . . Home Automation Network
HEVs . . . . Hybrid Electric Vehicles
ICEVs . . . . Internal Combustion Engine Vehicles
IEA . . . . International Energy Agency
IEC . . . . International Electromechanical Commission
IPC . . . . Initial Purchase Cost
MCP . . . . Market Clearing Price
MIBEL . . . . Iberian Electricity Market (*Mercado Ibérico de Eletricidade*)
OMI . . . . Iberian Market Operator (*Operador de Mercado Ibérico*)
OMIClear . . . . Clearing Platform for OMIP
OMIE . . . . Spanish side of the Iberian Market Operator
OMIP . . . . Portuguese side of the Iberian Market Operator
OTC . . . . *Over-the-counter*

PCR . . . . Price Coupling of Regions
PHEVs . . . . . . Plug-in Hybrid Electric Vehicles
PLDVs . . . . . . Passenger Light-duty Vehicles
RES . . . . Renewable Energy Sources
SAE . . . . Society of Automotive Engineers
SCADA. . . . . . Supervisory Control and Data Acquisition
SLH . . . . Spanish Legal Hour
SoC . . . . Battery State-of-charge
TOU . . . . Time-of-use Tariffs
TSOs . . . . Transmission System Operators
V2G . . . . Vehicle-to-grid
V2H . . . . Vehicle-to-home
V2V . . . . Vehicle-to-vehicle
XBID . . . . Cross-Border Intraday Market Project

Chapter 1

Introduction

1.1 Problem statement

The Paris Agreement, firmed in December 2015, established an important milestone regarding the global necessity to fight global warming and climate change. To address this problem, it is imperative to bring society together as a whole, i.e., governments, firms, scientists/researchers and the public must be summoned to give their contribution since this is a global problem. In this agreement, subscribed by the clear majority of the participant countries, the signatory parts pledged to cut their GHG emissions in order to limit the increase of the global temperature to a maximum of 2 ºC when compared to pre-industrial levels (UNFCC, 2015).

The International Energy Agency (IEA), in its latest outlook for EVs deployment (IEA, 2017), established two different GHG emission scenarios in which there is compatibility between two different carbon budgets and the targets defined in Paris. On the one hand, the IEA Two-degree Scenario (2DS) previews 1170 $GtCO_2$ of cumulative emissions between 2015 to 2100. Here, they state that there is a 50% chance of meeting the 2 ºC target. On the other hand, the IEA Beyond Two-degree Scenario (B2DS) establishes that there is a 50% chance to limit the temperature increase in 1.75 ºC by 2100, if only 750 $GtCO_2$ of cumulative emissions are verified. Both scenarios require that emissions must be null in the second half of this century (IEA, 2017).

The transportation sector is accountable for 23% of the total GHG emissions worldwide, hence the importance of intervening in this sector to meet the goals of the Paris Agreement (IEA, 2017). Electrification of private and public transportation is crucial to both the IEA scenarios (presented above). The 2DS estimates that the penetration electric passenger light-duty vehicles (PLDVs), i.e., electric private cars, will correspond to 10% of the total PLDV fleet by 2030 and to 60% of the total PLDV fleet by 2060; Concerning the B2DS scenario, it is expected that, by 2060, 85% of the PLDVs in circulation worldwide will be electric vehicles. The total PLDV fleet comprises both electric and internal combustion engine vehicles (ICEVs). PLDVs include passenger cars and passenger light trucks but exclude two-wheelers, three-wheelers, and low-speed/low-power four-wheeled vehicles (IEA, 2017).

Electric vehicles (henceforth referred as EVs) play an important role in the fight against global warming (since these vehicles don't emit directly any GHG) positioning themselves as a major tool to achieve the targets established in Paris. Moreover, the European Commission defined through Directive 2009/28/EC, mandatory goals (for each member-state) regarding renewable energy share increase, of at least 10%, in the transportation sector (European Comission, 2009a).

1.2 Research question and objectives

Given the previous problem statement, this dissertation was driven by the following research question:

> *How will electricity wholesale market prices change when an EV fleet acts as additional load to the power grid?*

Then, the objectives of this thesis are (i) to assess possible alterations of the electricity prices on the wholesale market, induced by different EV penetration scenarios and (ii) to identify the main impacts of EV penetration in Portugal's electricity generation mix and market operation.

1.3 Structure of the dissertation

This work is structured in five different chapters. Below, there is a brief description about each chapter:

- Chapter 1 introduces this dissertation problem statement—the necessity of EV penetration increase—and sets the proposed objectives;
- Chapter 2 comprises a review of the existent literature on EVs, its state-of-the-art and most recent findings, as well as a description and characterization of the Portuguese Energy System: its framework, MIBEL and the integration of European Electricity Wholesale Markets;
- In Chapter 3, the methodology adopted for this work is described and briefly explained;
- Chapter 4 provides the main results obtained from this study, followed by a discussion and interpretation of those same results;
- Finally, in Chapter 5, the main conclusions, research limitations and future perspectives are presented.

Chapter 2

Literature Review

2.1 The State-of-the-Art of Electric Vehicles

According to Yong et al. (2015), EVs can be beneficial to society in many ways: (i) enhance energy security, due to less dependence on fossil fuels to keep the transportation sector running, (ii) foster economic growth, given the necessity to develop specialized industries in order to answer to the increasing demand for EVs and (iii) safeguard environmental protection as EVs have zero tailpipe emissions and hence don't pollute (Yong et al., 2015).

2.1.1 EVs and associated technology

Since the invention of EVs, EV technology has been under permanent development and evolution, to fit the needs of EVs. Technology development focused on EV power train, batteries and EV charging infrastructure (Yong et al., 2015). To ensure that EVs improve their competitiveness (when comparing EVs with ICEVs), continuous research and development of novel technology for EVs is necessary (Yong et al., 2015).

Power train

According to their power train architecture and hybridization ratio, EVs are classified as hybrid electric (HEVs), plug-in hybrid electric (PHEVs) and battery electric (BEVs) (Yong et al., 2015):

- *Hybrid electric vehicles*: HEVs have two different kinds of engines, one electric and one internal combustion engine. However, these types of EVs cannot be plugged in to external energy sources, as the grid, and hence can't be charged. Nevertheless, HEVs' batteries have another way to be recharged, by the internal combustion engine or by transforming kinetic energy into chemical energy (that is stored in the vehicle's battery) in a processed named regenerative breaking. HEVs' vehicle efficiency can be improved up to 25% when compared to ICEVs (Tie & Tan, 2013).

- *Plug-in hybrid electric vehicles*: PHEVs' power train architecture is similar to the one found on BEVs, i.e., it has two types of propulsion (electric and internal combustion) but PHEVs' battery can be charged from an external electric source. PHEVs also have other different characteristics when compared to HEVs, namely the size of the battery (that is bigger than the HEVs' one). PHEVs' vehicle efficiency can be improved to 40% (Tie & Tan, 2013).
- *Battery electric vehicles*: as HEVs and PHEVs have two kinds of propulsion, BEVs only run on electrical power. An engine (motor) is connected to the battery that is charged both with regenerative breaking and recurring to an external electricity source, as the electrical grid. However, BEVs are more commonly used on cities since they are still lacking driving distance autonomy. However, BEVs present, in an environmental point of view, better performance than HEVs and PHEVs concerning GHG emissions (as BEVs only rely on an electrical engine) and thus are more environmentally friendly.

These power trains configurations enhance fuel economy and vehicle driving range due to their power motor efficiency and are better in these matters than ICEVs (Darabi & Ferdowsi, 2012).

Batteries

Batteries are the central component of EVs. In BEVs, batteries are the only propulsion sources and one of the two propulsion units in HEVs and PHEVs (Yong et al., 2015). EV battery technology evolution in the last decades has been remarkable: from lead-acid batteries to nickel-based, ZEBRA (or sodium-nickel chloride batteries) and most recently lithium-based batteries, to find new lightweight storage technologies, with greater energy and power density and that are inexpensive, safe and durable (Catenacci et al., 2013).

Chargers

As BEVs and PHEVs can be connected to external energy supply sources, BEVs' and PHEVs' power trains must have a charger linked to the batteries (Yong et al., 2015). This happens because the energy supplied from the power grid is in the altering current (AC) and EV batteries run in direct current (DC). Charging an EV battery can be accomplished following several different methods: the most common are constant current (CC), constant voltage (CV) and constant power (CP) charging (Yong et al., 2015).

Different international charging standards are available and are mainly defined by the countries where EV penetration shares are higher (Yong et al., 2015). The main charging standards are the SAE (Society of Automotive Engineers), IEC (International Electromechanical Commission) and CHAdeMO EV standard (Foley et al., 2010). Standardization of chargers can be categorized into different charging levels, according to IEC standard 6185-1 (Bessa, 2013):

- *Single-phase AC charging (low charging power)*: comprises AC level 1 (3 kW), which takes 12 hours to charge a 35 kWh EV battery, and AC level 2 (10 to 20 kW), which takes approximately 2 to 4 hours to charge a 35 kWh EV battery).
- *Three-phase AC charging (higher charging power)*: level 3 AC charging, i.e. fast charging, with charging power of 40 kW (45 minutes to charge a 35 kWh battery).
- *DC charging (fast charging)*: only feasible with a off-board charger and used in level 3 fast charging stations.

SAE J1772 standard defines 2 levels for both AC and DC charging levels. AC charging level 1 with 1.9 kW (120 V) and level 2 with 19 kW (240 V) (Bessa, 2013; Yong et al., 2015). DC charging level 1 with 36 kW(200–450 V) and level 2 with 90 kW (200–450 V) (Yong et al., 2015).

2.1.2 EV deployment perspectives

In 2016, new EV registrations/sales reached the 750 thousand units mark, setting a record of EV sales ever registered (IEA, 2017). From 2010 to 2016, the accumulated EV stock surpassed 2 million EVs circulating (considering PHEVs and BEVs).

More specifically, Norway is the country with the highest EV market share (29%), followed by the Netherlands (6.4%) and Sweden (3.4%). China, on other terms, leads the EV deployment campaign registering the largest EV market in 2016 and surpassing for the first time the USA as the world leaders in this regard and hence becoming the country with the highest EV stock (IEA, 2017). Moreover, European countries accounted for 215,000 new EV sales in 2016, with Norway, UK, France, Germany, the Netherlands and Sweden leading the effort (IEA, 2017).

The deployment scenarios for EV stocks in 2030—the EV30@30 campaign—estimate that by 2020, EV stocks worldwide will range from 9 to 20 million units (aggregated values) and reach 40 to 70 million units by 2025 (IEA, 2017).

2.1.3 The impacts of EV penetration

Yong et al. (2015) categorize the main impacts of a growing EV penetration into economic, environmental and technical. These impacts are not independent from each-other and are explained into more detail bellow.

Economic impacts

Economic impact assessment can be done considering two different perspectives: (i) from the power grid point of view and (ii) from the EV consumer point of view (Richardson et al., 2010):

- From the power grid point of view, EVs represent an additional load to the power grid as EVs must be charged periodically (IEA, 2017). In order to respond to an increasing demand for electricity, more energy supply capacity will be needed and investments on adittional capacity represent additional costs (Talebizadeh et al., 2014). Also, during the energy transmission process (from the power grid to the EV fleet), there are a considerable power losses (Yong et al., 2015). However, this situation can be avoided if different strategies of charging are adopted, as shown by Lyon et al. (2012).
- According to the consumer perspective, as EVs have very efficient engines (motors) and electricity prices are generally low, EV maintenance is cheap and hence it makes EV purchasing interesting for potential consumers (Windecker & Ruder, 2013). On the other hand, the initial purchase cost (IPC) of an EV is higher when compared to the IPC of an ICEV due to the EV battery cost (Thiel et al., 2010). To reduce the EV IPC, a variety of policies can implemented, such as EV mass production (Gass et al., 2014), energy trading policies (Lunz et al., 2012) or efficient charging policies (Karabasoglu & Michalek, 2013).

In conclusion, the economic impacts of a higher EV penetration are overall negative. Power grids need more installed capacity to respond to demand peaks (peak-loads) and EV IPCs are still high (Yong et al., 2015). Moreover, a handful of measures can be implemented to reduce the economic impacts of EV deployment: smart charging of EVs, energy trading incentives and more efficient energy policies; achieving this, it is possible to deploy EVs in a sustainable way and also to reduce the EV payback periods as suggested by Yong et al. (2015).

Environmental impacts

As pointed out before, EVs (and more precisely BEVs) are considered as environmentally friendly, since there aren't any direct GHG emissions from these vehicles, i.e., zero tailpipe emissions. However, this isn't entirely true: the electricity used by BEVs may not be generated by renewable sources as it depends on each region's energy production/generation mix (Yong et al., 2015).

To evaluate the total GHG emissions between EVs and ICEVs, from a life-cycle assessment perspective, a wells-to-wheels methodology can be adopted. This kind of methodology takes into consideration all the GHG emissions during the life cycle of an EV (Edwards et al., 2004) and has been widely implemented by many authors (for e.g. Faria et al. (2012, 2013); Ma et al. (2012)).

Nanaki & Koroneos (2013), Windecker & Ruder (2013) and Lorf et al. (2013) concluded that EVs present lower well-to-wheels emissions when compared to ICEVs. Nevertheless, one must consider the origin of the energy supplied to the EVs in order to get the full picture about the total GHG emissions from a life cycle assessment perspective: Sioshansi & Miller (2011) and Weiller (2011) present situations where EV wells-to-wheels emissions were higher than ICEVs' GHG emissions; this happened due to the electricity generation mixes from each studied region were heavily based on non-renewable energy sources. These findings reinforce the idea that one of the most important sectors to improve environmental sustainability of EV deployment are in fact the electricity generation mixes.

Another environmental impact of is related to higher EV deployment is the rising demand for commodities, needed for EV battery manufacture (IEA, 2017). Understanding commodity distribution, availability, and monitoring these commodities' prices, alongside with minimization of environmental impacts of their exploration and industrial transformation, are of the utmost importance for environmental and economic prosperity of EV markets (IEA, 2017).

In conclusion, EVs are not GHG emission free, even though BEVs don't emit any tailpipe emission. In regions where carbon-based energy sources dominate, wells-to-wheels emissions of EVs can be higher than those verified on ICEVs (Yong et al., 2015). Nevertheless, as renewable energy sources are increasing its penetration into electricity production mixes all over the world, it is expected that wells-to-wheels GHG emissions of EVs will decrease (Yong et al., 2015).

Impacts on the power grid

Alongside with economic and environmental impacts, EVs also present technical impacts on the power grid (from now on referred as "the grid"). Perhaps the most important negative impact is related to the additional load experienced by the grid (Yong et al., 2015). Dharmakeerthi et al. (2011) and Green et al. (2011) identified some negative impacts that an increasingly larger EV fleet can have on the grid. Although technical problems are extremely important to assess, this dissertation will focus only on the increasing demand for energy generated by EV fleets (other technical impacts of EVs on the grid, namely impact on system components, impact on system losses, impacts on voltage profile and phase unbalance, harmonic impacts and finally stability impacts are discussed by Yong et al. (2015) (pp. 373–375).

Weiller (2011) studied the daily load profiles of EV fleets in the USA and concluded that, if there aren't any time and place restrictions to EV charging, the resulting load profiles would increase in peak hours. These peak hours correspond to the working hours (when people arrive at work) and at the end of the working day (when people arrive home) — to prevent these increased loads on the grid at peak hours, a "delayed charging control" is proposed.

Other studies on the EV impacts on the grid have been made in different countries. Hartmann & Özdemir (2011) researched about potential impacts of EV charging into the German electricity grid in 2030. The results showed that uncontrolled charging of an EV fleet comprised by one million EVs, would only cause a 1.5% increase in the daily peak load profile. Nevertheless, if the considered EV fleet matched the entire German ICEV fleet (42 million vehicles), then the correspondent daily demand for electricity (measured by the peak load increase) would increase twofold (Hartmann & Özdemir, 2011). Since national grids are not prepared to such drastic changes in the transportation sector, Hartmann & Özdemir (2011) suggest that using a million EV fleet as grid stabilizers (*grid stabilizer storages*) would reduce to a maximum of 16% the daily peak load of a 42 million unit EV fleet.

Another study, carried out by Drovtar et al. (2013), assessing the impacts of integrating EVs into the grid, took place in Estonia where the EV penetration ratio is 30% of the total PLDVs nationwide. The results obtained show that integrating the EV fleet has a minor impact on the power load supported by the Estonian grid: uncontrolled charging accounted for a 5% increase and controlled charging was responsible for only 4% (Drovtar et al., 2013).

The International Energy Agency's report on EV deployment proposes three options for mitigating negative impacts on the grid arisen from EV charging (IEA, 2017).

- Firstly, build and deploy charging infrastructure that minimizes any negative impact, i.e. installation of local charging points at homes and businesses (connections from the low-voltage grid). Additional power demand may require contracting more higher power capacity tariffs and reinforcing the infrastructure for energy supply at the connection points.
- Secondly, give incentives to end users maximize self-consumption through home-based power generation (e.g. installed solar panels).
- Finally, as EV deployment increases, charging infrastructure standards must be designed to make EV charging process interoperable. This is necessary for EV integration (the "physical-electricity-network") side and to the information and technology side (IEA, 2017).

Summing up, impacts on the power grid load profiles are due to future increase in demand for energy, since EVs are additional loads to the grid (Yong et al., 2015). A handful of research works was able to identify specific hours (critical hours) for EV energy consumption from the grid: when arriving at work (morning) and when arriving home (evening). The additional loads could be troublesome to the national grids, given the limited installed capacity, may not be able to supply enough energy to large fleets of EVs. Nevertheless, some measures and policies are being designed to respond to these problems: the implementation of time-of-use (TOU) tariffs is one example (Park et al., 2013), different efficient charging management strategies (Weiller, 2011; Hartmann & Özdemir, 2011; Drovtar et al., 2013) and other policy measures (IEA, 2017).

2.1.4 EVs and smart grids

With increasing EV penetration, power grids are subject to additional loads and as seen previously, negative impacts of EV deployment and interconnection to the grid are being studied (Yong et al., 2015). Simultaneously, the increasing deployment of EVs can be viewed as an opportunity to develop novel and more sustainable power grid designs, as smart grids (Yong et al., 2015).

Ancillotti et al. (2013) define smart grids as power grids that use computer-based control and automation in order to improve reliability, sustainability and efficiency of power supply. Bidirectional communication, supported by information and communication technology in the power grids, ensures links between utility firms and consumers (Bhatt et al., 2014; Yong et al., 2015). Moreover, smart grids can monitor and optimize, in an autonomous and intelligent way, the operations between every component of the grid (Sinha et al., 2011). Smart grids promote the participation of customers in the grid's operation and improve the grid reliability and power quality (Yong et al., 2015).

The main features of smart and conventional grids, are shown in Table 2.1. The most important feature of smart grids is the bidirectional path of communication. Bidirectional communication enabled the development of a variety of smart grid applications like infrastructure metering, home automation networks, demand response and distributed generation integration as shown in Figure 2.1 on page 12.

Table 2.1: Comparison between conventional and smart grids (Yong et al., 2015).

Characteristics	**Conventional**	**Smart grid**
Communication	Uni-directional	Bi-directional
Smart sensors and meters	Limited	Throughout the grid
Consumer participation	Passive	Active
Power generation	Centralized	Distributed
Energy recovery	Manual	Self-healing

Yong et al. (2015) summarize the principal smart grid's features:

- *Advanced metering infrastructure (AMI)*: is a technology that collects energy consumption information in real-time (from the demand side) and enables grid operators to use the retrieved data to better manage electricity demand in the power grid.
- *Supervisory control and data acquisition (SCADA)*: central system that establishes connection between the smart grid's real-time monitoring devices as well as controlling other equipment, through bi-directional communication.

- *Home automation network (HAN)*: infrastructure that controls different electric elements (similar to AMI) at a house-scale. HAN and AMI are complementary in the sense that the information retrieved by AMI is communicated to HAN and, depending on market and grid state, allows HAN to manage in the best possible way energy consumption of the connected electric appliances in the household.
- *Demand response*: allows costumer/public participation in smart grid operation through incentives, i.e. energy generation in households and businesses, and thus decreasing grid stress during peak load periods (Yong et al., 2015). Hence, demand response can prevent additional energy generation in peak load periods (caused by EV fleet charging), proving to be a cost-effective solution in power grid operation (Siano, 2014; Rahimi & Ipakchi, 2010).
- *Grid distributed energy generation*: contrary to conventional power grids, smart grids rely on energy produced by dispersed generation units within the grid's framework, which can reduce power loss from energy transmission in the case of conventional grids. Moreover, RES are being employed in smart grids as distributed generation sources, alongside storage technologies to aid these power sources storing excess energy produced. Finally, using RES as energy generation distribution sources could be more environmentally sustainable to power grids.
- *Vehicle-to-grid technology*: With the maturation of smart grid technology, vehicle-to-grid (V2G) technology (both uni and bi-directional V2G) is becoming increasingly common as EV deployment rises (Yong et al., 2015). Thus, V2G is important for EV integration into smart grids. Bhatt et al. (2014) state that V2G will be feasible if energy control and management within the power grid and EV batteries is done. This technology is beneficial to the power grid in many regards, if good management practices are followed (Yong et al., 2015). Nevertheless, large EV fleets may raise a number of problems to the grid such as the different states of charge of each EV (Yong et al., 2015). Bi-directional V2G is comprised by three different kinds of energy transmission/transfer technology—vehicle-to-home (V2H), vehicle-to-vehicle (V2V) and vehicle-to-grid (V2G) (Yong et al., 2015). V2H is the smallest (scale wise), as it only applies to home automation networks: here, EVs can be used as energy storages for when home renewable energy production (supply) exceeds demand and as power suppliers when home renewable generation is insufficient (demand) (Berthold et al., 2011). On another scale (like parking lots in businesses, EV aggregators are fundamental to coordinate energy exchange between EVs and the grid and through EVs (Liu et al., 2013). V2G enables energy transfer from the grid to charge EVs and the inverse flow is also possible, i.e. EV fleets can support the grid (Ghosh et al., 2013; Yilmaz & Krein, 2012). Thus, V2G is beneficial to the power grid, as it helps in a handful of situations such as peak

shaving, load levelling and voltage regulation (Yong et al., 2015).

2.2 The Portuguese electric system

At the end of 2016, the Portuguese electricity generation capacity (installed capacity) accounted for a total of 19,518 MW. On the one hand, installed renewable generation facilities represent 66.84%, i.e. 13,046 MW: hydro and small hydro contribute with 6,945 MWh, wind power has an installed capacity of 5,046 MW, biomass follows with 615 MW and finally, solar with 439 MW. On the other hand, conventional energy sources represent 33.16% (6,473 MW) of the total installed capacity: 4657 MW for natural gas (828 MW cogeneration), 1756 MW for coal and 60 MW for other non-renewable sources (REN, 2016) In terms of electricity generation mix, Table 2.2 summarizes the electricity generation sources for 2016 and 2017. It is important to analyse the main differences regarding renewable electricity generation in both years. In 2016, hydro accounted for 28% of the total generation mix and, as previously referred, hydro power has great importance to the Portuguese electricity production. Due to climacteric conditions in 2017 (dry year), hydro generation represented only 10% of the total electricity generation (5,169.77 GWh). Other RES maintained their share from 2016 to 2017 and non-renewable generation sources weighted more in 2017.

Table 2.2: Electricity generation mix in 2016 and 2017. Data source: REN (2018).

Production by source type (GWh) in 2016 (Total = 54,500.99 GWh)			
Renewable sources		**Conventional sources**	
Hydro	15,151.68	Coal	11,739.17
Wind	12,189.38	Natural Gas	7,435.15
Biomass	2,675.90	Others	4,526.98
Solar	782.73		
Total	30,799.69		23,701.30

Production by source type (GWh) in 2017 (Total = 52,440.7 GWh)			
Renewable sources		**Conventional sources**	
Hydro	5,169.77	Coal	13,625.76
Wind	11,972.89	Natural Gas	13,530.39
Biomass	2,811.23	Others	4,481.32
Solar	849.34		
Total	20,803.23		31,637.47

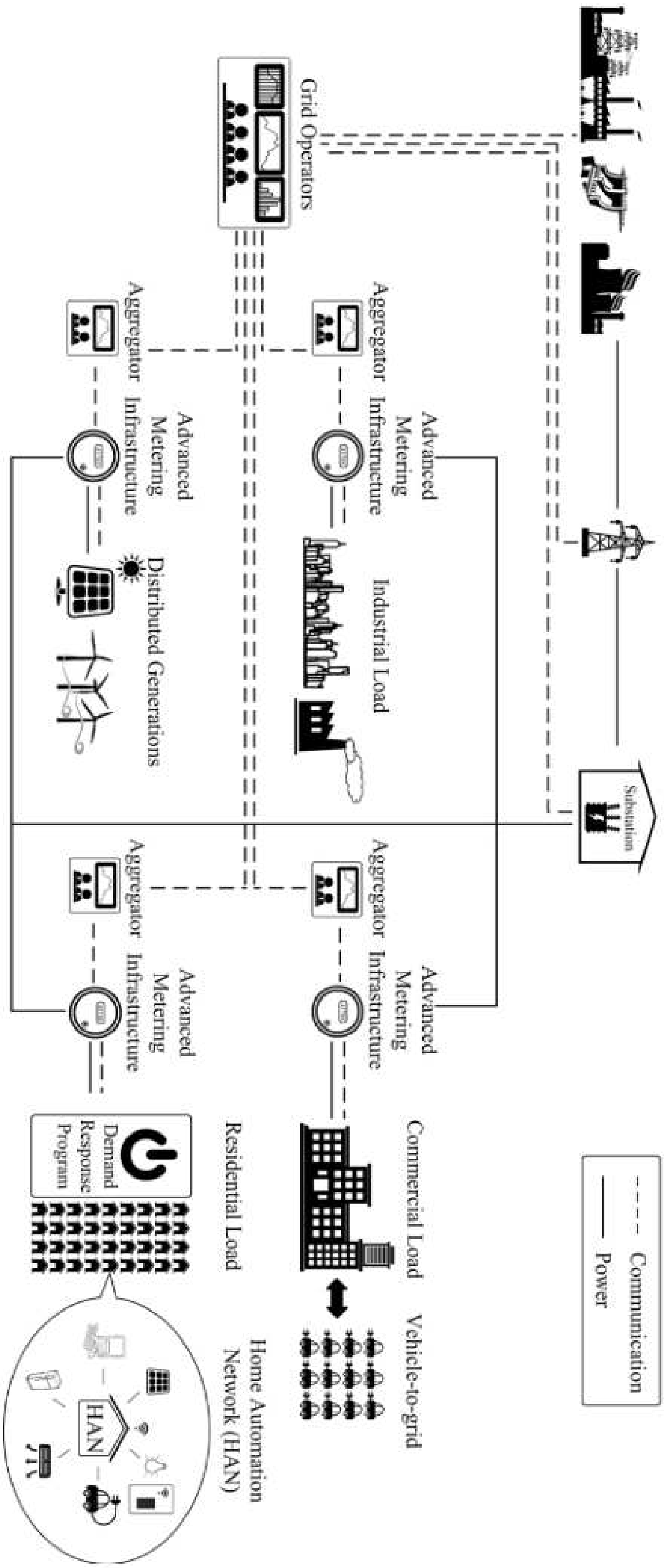

Figure 2.1: Smart grid framework (Yong et al., 2015): the different smart grid applications are represented in this schematic picture.

2.2.1 MIBEL

In 1998, Portuguese and Spanish governmental authorities agreed to create a single Iberian Electricity wholesale market (MIBEL) to foster free competition to energy producers and traders of the region (MIBEL, 2017). In 2004, the Santiago de Compostela Agreement was signed, and thus begun the market integration process and the creation of MIBEL. This market had, in its foundations, the objectives of transparency, objectivity and a free competition environment. Also, MIBEL was supposed to be able to generate financial liquidity and to be able to auto-organize itself (MIBEL, 2017). Finally, in July 2007, MIBEL begun its official market operation, thus concluding the harmonization process started in 1998 (MIBEL, 2017).

During the negotiations, it was defined that MIBEL would be managed by a market operator, OMI (*Operador de Mercado Ibérico*). Subsequently, OMI is divided into three different managing institutions (MIBEL, 2017)

- *OMIE*: the Spanish part of OMI. OMIE is responsible for managing the spot markets (day-ahead and intraday markets), for electricity price management and responsible for the liquidation of the commercial transactions of MIBEL.
- *OMIP*: the Portuguese part of OMI. OMIP is responsible for managing MIBEL's derivatives/forwards markets (futures, forwards and SWAP), contributing to the development of MIBEL, to promote reference prices, to develop efficient risk management tools and to overcome limitations of the OTC (*over-the-counter*) market.
- *OMIClear*: is the Clearing Platform for OMIP, its mains objective resides on clearing, registration, risk management and settlement of OMIP's transactions.

Day-ahead market

MIBEL's spot market is the platform where energy trading takes place to the day after the negotiation (day-ahead market). This market establishes hourly prices (for each 24 hours of the day) through the whole year (365/366 days). OMIE is responsible for the management of the spot market and the reference negotiation hour is the Spanish legal hour (SLH) (ERSE, 2017).

Day-ahead market price is formed through aggregation of the biding offers (to purchase or to sell electricity) by the registered participating agents in MIBEL. Each agents' bid indicates the day and hour, the price and the quantity of electricity one wants to purchase (ERSE, 2017). Then, every selling bid is ordered by crescent value (supply curve) and all the purchasing bids are ordered by decreasing value (demand curve), for every hour of the day. The market price, i.e. Market Clearing Price (MCP) is found by crossing the supply against the demand curve. This ensures that the day-ahead market price is the lowest possible for which the supply corresponds to the demand (see Figure 2.2) (ERSE, 2017).

Since the spot market comprises both the Portuguese and Spanish national markets, it is

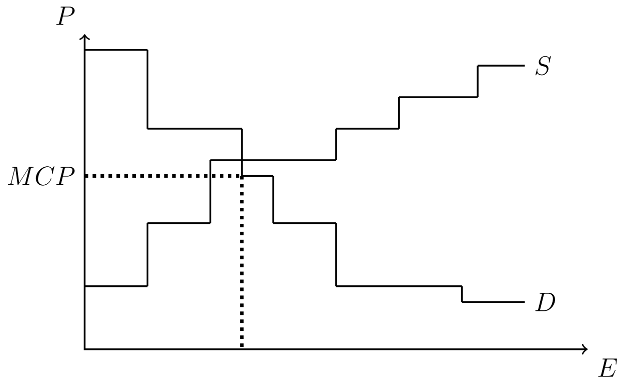

Figure 2.2: Spot market price formation for a specific hour. As it is possible to see in this figure, MCP is the lowest price where the supply curve (S) crosses the demand curve (D); P is represents the price and E the energy traded.

imperative to understand and monitor when the transmission capacity between the two countries is limited or constrained. If transmission is constrained, national markets are separated and prices are formed for each country or area (market splitting) (ERSE, 2017). Transmission constraints could be due to many reasons such as (i) structural organization of each area operation, (ii) insufficient transmission/linking capacities or (iii) agent behaviour. For the aforementioned reasons, supervision is important to minimize market splitting and to ensure that any disloyal competition between market participants/agents is prevented (ERSE, 2017).

MIBEL's intraday market is complementary to the day-ahead market: electricity is traded between each hour in order to adjust the quantities of energy traded in the day-ahead market (spot market). Intraday market comprehends 6 daily negotiation sessions. Each intraday session generates the price for each negotiation hour taking place at each session (ERSE, 2017).

Market results

Results for 2016 and 2017 show that MIBEL is a robust market and so far, has been functioning well. As seen in Figure 2.3, through the year, there were several market splitting situations. Nevertheless, the majority of prices follows a linear trend, meaning that Spanish and Portuguese prices were the same.

In 2016, MIBEL's prices ranged from 0–75 €/MWh in Portugal and 2.30–75.50 €/MWh in Spain. The Portuguese average price was 39.44 €/MWh and the Spanish average price was 39.67 €/MWh. The price average difference between the Spanish and Portuguese price was 0.23 €/MWh. In 2017, MIBEL's prices ranged from 8–101.99 €/MWh in Portugal and 2.30–101.99 €/MWh in Spain. The Portuguese average price was 52.48 €/MWh and the Spanish average price was 52.24 €/MWh, which accounts for an average difference in price of 0.24 €/MWh.

(a) Market splitting occurrences in 2016. **(b)** Market splitting occurrences in 2017.

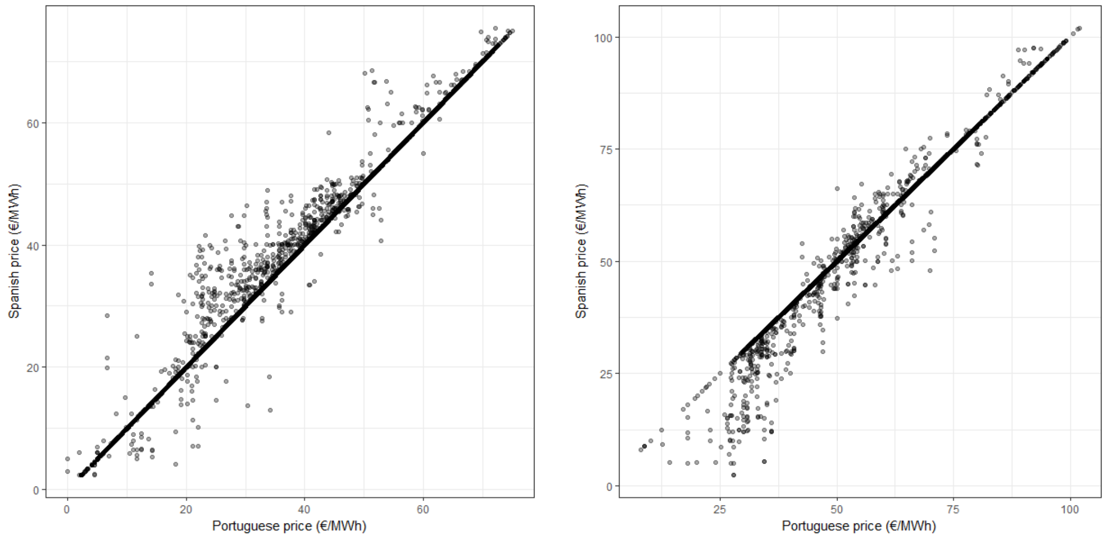

Figure 2.3: Market splitting in 2016–2017: (a) market splitting occurrences in 2016 and (b) market splitting occurrences in 2017. Data source: REN (2018).

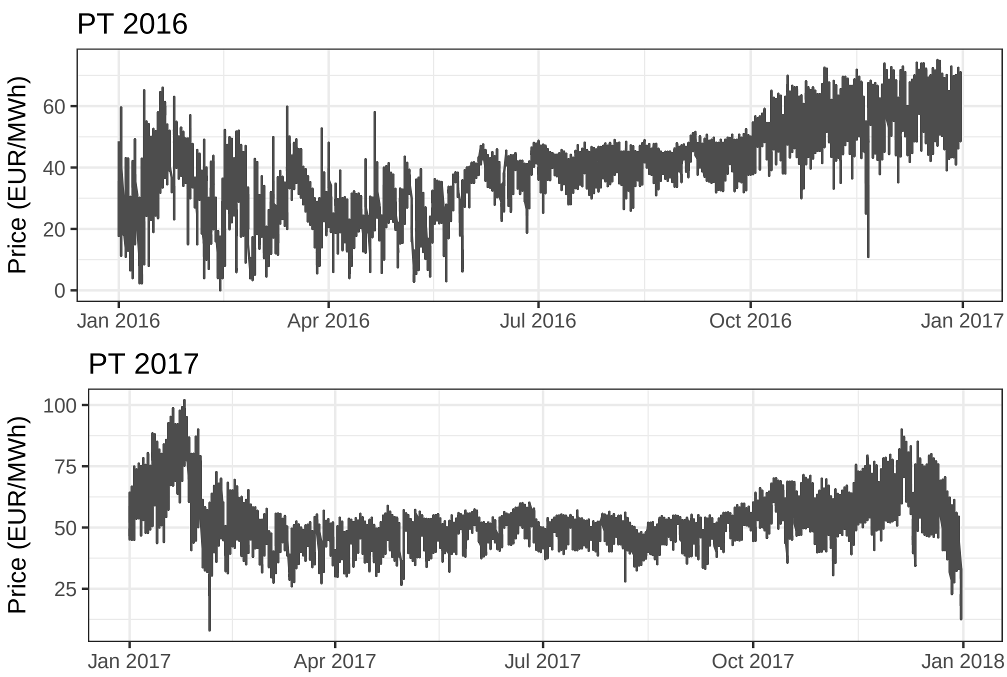

Figure 2.4: Portuguese price time series for 2016–2017. Data source: REN (2018).

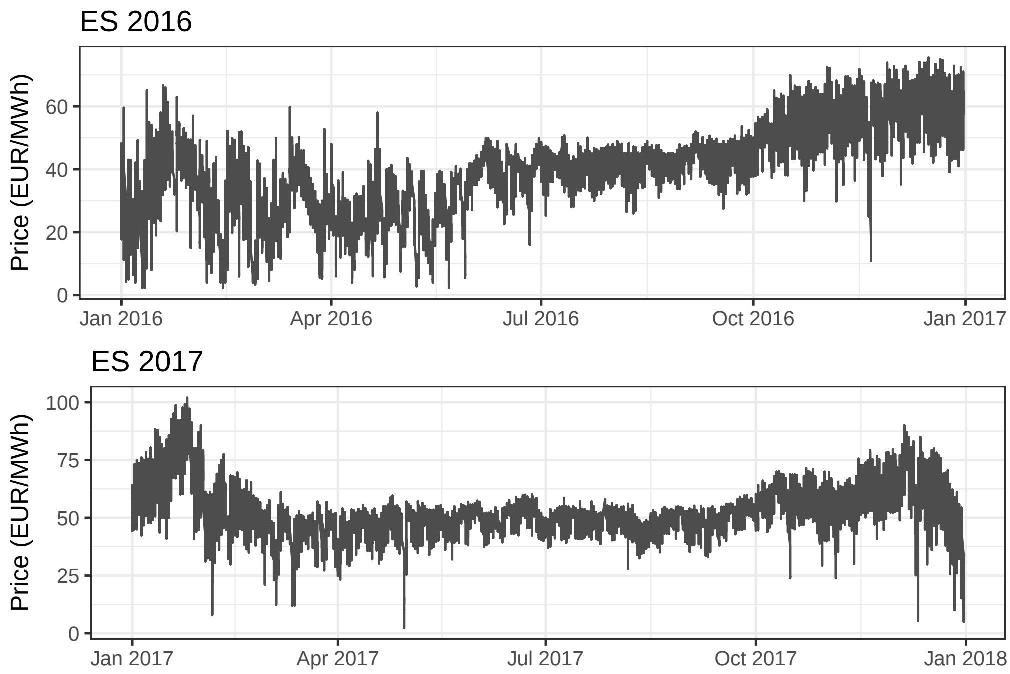

Figure 2.5: Spanish price time series for 2016–2017. Data source: REN (2018).

The time series graphs depicted in Figures 2.4 and 2.5 show that for each country, the general trend in prices was somewhat similar for each year. Moreover, it is important to reinforce the difference in prices from 2016 to 2017:

- As 2016 was rainy year, hence a year with high renewable production (mainly from hydro generation), average prices were lower.
- On the other hand, 2017 was a dry year, with scarce precipitation and, in opposition to 2016, renewable generation was lower. This means that, in order to meet the demand, conventional power generation plants had to produce additional energy. Conventional power plants have higher costs than renewable generation and hence the increase in the average price (13.04 €/MWh in Portugal and 12.57 €/MWh in Spain).

Nevertheless, with the available data, it is noticeable that MIBEL is functioning well, as average prices in Portugal and Spain don't vary much (as seen with graphic plotting of market splitting occurrences and time series profiles between the two countries for two different years).

2.2.2 Integrating regional markets into a single European market

Following the EU intention to create a single European electricity wholesale market (European Comission, 2009b), the European Power Exchanges (EPX) started a joint project—the Price Coupling of Regions (PCR)—whose central aim is to calculate the day-ahead prices of electricity across Europe, taking into account the installed capacity of transmission infrastructure (EPEX SPOT, 2017). PCR is currently being operated by seven EPXs: EPEX SPOT, GME, Nord Pool, OMIE, OPCOM, OTE and TGE (EPEX SPOT, 2017). Hence, the participating countries are Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and UK (EPEX SPOT, 2017).

Three main pillars are the base of the PCR project (EPEX SPOT, 2017)

- A single algorithm—EUPHEMIA—solves the market coupling problem on the PCR perimeter and maximizes the overall welfare of the solution obtained, as well as promoting transparency (EPEX SPOT et al., 2016).
- Decentralized data-sharing, essential to a robust operation.
- The *PCR Matcher & Broker* service, that ensures anonymity of exchange orders and constrains in the participating power exchanges in order to calculate the bidding zone prices (and other reference prices).

Intraday markets integration is also important to achieve a single European market. The European Commission designed a Target Model for intraday, ”based on continuous energy trading where cross-zonal transmission capacity is allocated trough implicit continuous allocation” (EPEX SPOT, 2018). To date, EPEX SPOT, GME, Nord Pool Spot and OMIE have already established transparent and efficient intraday markets with cross-border trading capacity (EPEX SPOT, 2018).

XBID Market Project is a joint integrated intraday cross-zonal test between national Transmission System Operators (TSOs) and EPXs, whose aim is to ensure continuous intraday trading in the EU and intended to integrate regional intraday markets into a single European intraday platform (EPEX SPOT, 2018). Similarly to the PCR project, XBID will work recurring to an IT solution and information on transmission capacities (provided by the TSOs) (EPEX SPOT, 2018). Finally, XBID is designed to support both explicit and implicit continuous trading and follows the target established by the EU for an integrated European intraday market (EPEX SPOT, 2018).

2.3 The Portuguese EV initiative

Decree-Law 39/2010 created the legal and infrastructural conditions for EV deployment and regarding the recharging system for EVs, as well as the guidelines to the creation of a national pilot project for electric mobility charging stations network (Ministério da Economia, da Inovação e do Desenvolvimento, 2010).

The organization of the system for electric mobility comprises three main activities, present on Decree-Law 39/2010 (Ministério da Economia, da Inovação e do Desenvolvimento, 2010):

- *Electricity retailing for EV charging*: wholesale acquisition and retailing of electricity to supply the EV fleet throughout the charging network, performed under competition in which every interested agent should require a license in order to operate nationwide.
- *Installation, operation and maintenance of the charging stations*: this activity is subject of regulation for a transitory timespan, being opened to competition in the future.
- *Mobility network operations management*: responsible for energy and financial management of the EV charging network. This activity is regulated and will remain so, not being opened to competition.

MOBI.E

Following the directives mentioned above, MOBI.E is the pilot electricity charging network program. MOBI.E initiative is present in more than 50 municipalities all over Portugal (including Madeira) and accounts for more than 1250 charging stations (MOBI.E, 2018a).

The uniqueness of MOBI.E makes it a success when compared to other electric charging network programs across Europe — in their work, (Pinto et al., 2010) make a comparison between MOBI.E and the well-known Better Place project[1]. Better Place's business model was a "closed" system, based on package sales, i.e., they sold the vehicle, batteries and the recharging possibility (Pinto et al., 2010). From this business approach, gigantic market entry barriers were formed, reducing policy definition and hence arising disadvantages for end-users (Pinto et al., 2010).

On completely different terms, MOBI.E adopted an open-access business model, where any car and battery manufacturer, retailer and operator can participate in the EV recharging network market (Pinto et al., 2010; Ministério da Economia, da Inovação e do Desenvolvimento, 2010). Moreover, MOBI.E allows the integration of all stakeholders, information, energy and financial flows which, according to Pinto et al. (2010), reduces the transaction costs. Finally, the MOBI.E business model has low initial investment costs which translates in reduced barriers to entry and stimulate the growth of the EV recharging network market (Pinto et al., 2010). Due to the success of the MOBI.E initiative, many car manufacturers, operators and retailers are now operating in the EV recharging network: Energias de Portugal (EDP), Galp, Prio, Repsol an others (MOBI.E, 2018b).

Tesla superchargers

Tesla entered the EV charging business and is installing superchargers in North America, Europe, Middle East and Asia; at the moment, 1191 charging points with 9184 superchargers available worldwide (Tesla, 2018). The charging lasts about 30 minutes and the supercharging

[1]Better Place filed for bankruptcy in Israel in May 2013 (Kershner, 2013; Woody & Quartz, 2013).

is less expensive than filling an ICEV's fuel tank, making Tesla's supercharging infrastructure possible solution to most EVs lack of electric drive range.

In Portugal, there are already two operational stations, Fátima Supercharger and Montemor-o-Novo Supercharger, and five more supercharging stations are expected to open by the end of 2018 in Braga, Vila Real, Guarda, Castro Verde and Faro (Tesla, 2018).

Chapter 3

Methodology

3.1 Data

The data used for this work is available to the public, as a matter of transparency and to allow reproducibility of this type of research. A brief description of the data is presented bellow:

- For estimation of the future EV fleet, data from Associação Automóvel de Portugal (ACAP) was collected (https://www.acap.pt/index.php?route=base/pt/pagina/36/estat%C3%ADsticas/). This data refers to the circulating ICEVs in Portugal. By the end of 2010, ACAP registered 5,685,000 ICEVs in Portugal. Thus, in this work, the different penetration scenarios will be based on this number. Hence, scenario 1 is comprised by 56,850 EV (1% of the total EV fleet), scenario 2 by 284,250 EVs (5%) and scenario 3 by 568,500 EVs (10%).
- Historical bid offers data for day-ahead market (years 2016 and 2017) was retrieved from OMIE (http://www.omie.es/aplicaciones/datosftp/datosftp.jsp?path=/curva_pbc_uof/). Only data concerning the portuguese wholesale market was gathered. The total entries analysed were 2,401,472 (1,163,752 for 2016 and 1,237,720 for 2017).
- Electricity load data (years 2016 and 2017) was retrieved from REN (http://www.mercado.ren.pt/PT/Electr/InfoMercado/Consumo/Paginas/Verif.aspx). The total entries analysed were 2,401,472 (1,163,752 for 2016 and 1,237,720 for 2017).

3.2 Developed model

To evaluate day-ahead market price change, a simulation model was developed. In this model, EVs represent an additional load to electricity comsumption and thus MCP alterations were expected. It was also considered that, in order to meet the additional load demand, it was necessary to buy more energy, in form of blocks, in a sequential way, i.e. blocks are ordered by crescent price values and these blocks must be purchased in a sequential order until meeting the new load demand.

3.2.1 Model assumptions

Due to limited time, some assumptions had to be made in order to make the developed model feasible. These assumptions focus mainly in the performance of EVs and associated equipments (EVSE) but also in driver's habits and behaviour.

EV specifications

- All EVs considered in the model are BEVs (full electric vehicles).
- EV battery capacity (α) is assumed to be 24 kWh (0.024 MWh). This was calculated as the average battery capacity value of the all BEV list present in Perujo & Ciuffo (2010) and is in line with the values used by other authors, as Jain & Jain (2014).
- At the time of their arrival home and begin charging, all EVs are considered full drained/empty, i.e., their batteries' State-of-Charge (SoC) is 0%.

Charging habits and behaviour

- EV load profiles are the same for each day (week and weekends) and throughout the year (for each considered year, 2016 and 2017), i.e. seasonality behaviours are not considered.
- All vehicles are charged at home. Home arrival time, which corresponds to specific hour (h), $h \in \{17, 18, \ldots, 24\}$, is not arbitrary.
- In fact, it was assumed that all EVs were to be charged between hours 17 and 24, following a normal distribution as seen in Figure 3.1 and Table 3.1, and were the charging peak is around $h = 21$. This follows the trend observed in the load profiles historic data from 2016 and 2017, where the peak load was around 20–23h (see Figure 3.2 on page 25).

Table 3.1: Charging hours used for the simulation.

Charging hour (h)	Charging EVs (%)
$h \in [17, 18[\Rightarrow h = 17$	0.14
$h \in [18, 19[\Rightarrow h = 18$	2.14
$h \in [19, 20[\Rightarrow h = 19$	13.59
$h \in [20, 21[\Rightarrow h = 20$	34.13
$h \in [21, 22[\Rightarrow h = 21$	34.13
$h \in [22, 23[\Rightarrow h = 22$	13.59
$h \in [23, 24[\Rightarrow h = 23$	2.14
$h \in [24, 01[\Rightarrow h = 24$	0.14

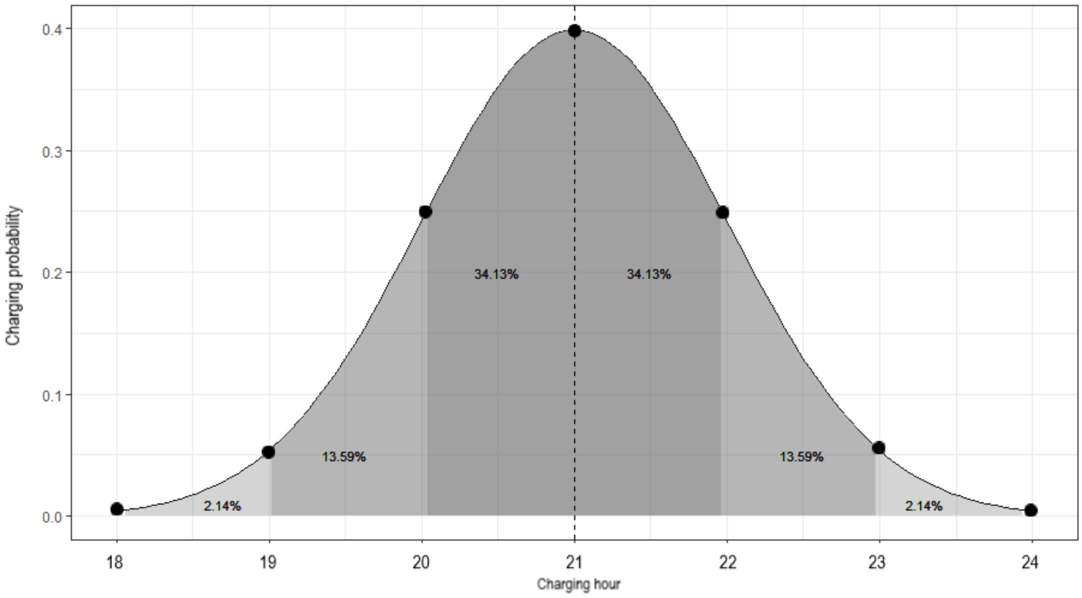

Figure 3.1: Hourly charging profile used for the simulation. Charging probability follows a Gaussian (normal) distribution.

3.2.2 Mathematical description of the simulation model

Let the number of EVs charging at a given hour h be denoted as N_h^c. Then, we have that, for a total number of N EVs existing in the market, i.e. a specific EV penetration scenario, and a ratio ρ_h that expresses the fraction of vehicles being charged at the same hour:

$$N_h^C = N\rho_h \tag{3.1}$$

These vehicles charging at specific/arbitrary hour h induce an additional load to the grid:

$$L_h^E = N_h^C \alpha \tag{3.2}$$

where $\alpha = 0.024$ MWh.

Naturally, the total grid load is the sum of all present loads:

$$L_h = L_h^0 + L_h^E \tag{3.3}$$

where L_h^0 is the load without EVs, i.e. "conventional" load (historic data).

Considering the the dynamics of the electricity wholesale market for a specific hour, let us describe the process through which the MCP is obtained. Firstly, we need to define mathematically the traded energy blocks. These blocks are represented as vectors with two coordinates (energy load and associated price):

$$\mathbf{b}^i = (\ell_i, p_i) \tag{3.4}$$

With this in mind, let us define how the total load trend in the market is the sum of all the loads traded as energy blocks:

$$L_h = \sum_{t=1}^{T} \mathcal{L}_t \tag{3.5}$$

where t denotes the transaction, T the final transaction and $\mathcal{L}_t$ the additional energy traded in transaction t.

Take the set of all transactional blocks at the time when transaction t will occur:

$$\mathcal{B}_t^h = \{b_1, b_2, \dots\} \tag{3.6}$$

It is obvious that, as blocks are traded, a recursive relationship emerges:

$$\mathcal{B}_{t+1}^h = \mathcal{B}_t^h \setminus \{\mathbf{b}^t\} = \mathcal{B}_t^h - \mathbf{b}^t \tag{3.7}$$

$\mathcal{B}_1^h$ is the the set of all available blocks when the market opens at each hour h. Considering this, we have that

$$\mathcal{L}_t = \ell_t \equiv b_\ell^t \tag{3.8}$$

where

$$\mathbf{b}^t = \{\mathbf{b} \in \mathcal{B}_t^h : b_p = \min(b_p^i)\} \tag{3.9}$$

Note that the price paid for the block traded in transaction t, Π_t, is also similarly given by

$$\Pi_t = \min_i \{b_p^i : b^i \in \mathcal{B}_t^h\} \tag{3.10}$$

Finally, to get the new MCP (Π_T), we have to find the last transaction for which the new demand caused by the charging EVs in the specific hour h was completely supplied. Hence, to find Π_T, the following system must be respected:

$$\begin{cases} b^T \in \mathcal{B}_T^h & (3.11a) \\ b_\ell^T \geq L_h - \sum_{t=1}^{T-1} \mathcal{L}_t & (3.11b) \\ b_p^T = \min_i (p_i) & (3.11c) \end{cases}$$

Translating, when the sequential buying dynamics (buying the cheapest blocks first) finally let us reach the load needed to supply de EV generated additional demand, we have obtained the final transaction and thus:

$$\Pi_T = b_p^T \tag{3.12}$$

The previous calculation is done numerically and only applies to $L_h^E (L_h^E = \sum_{t=1}^{T} \mathcal{L}_t)$.

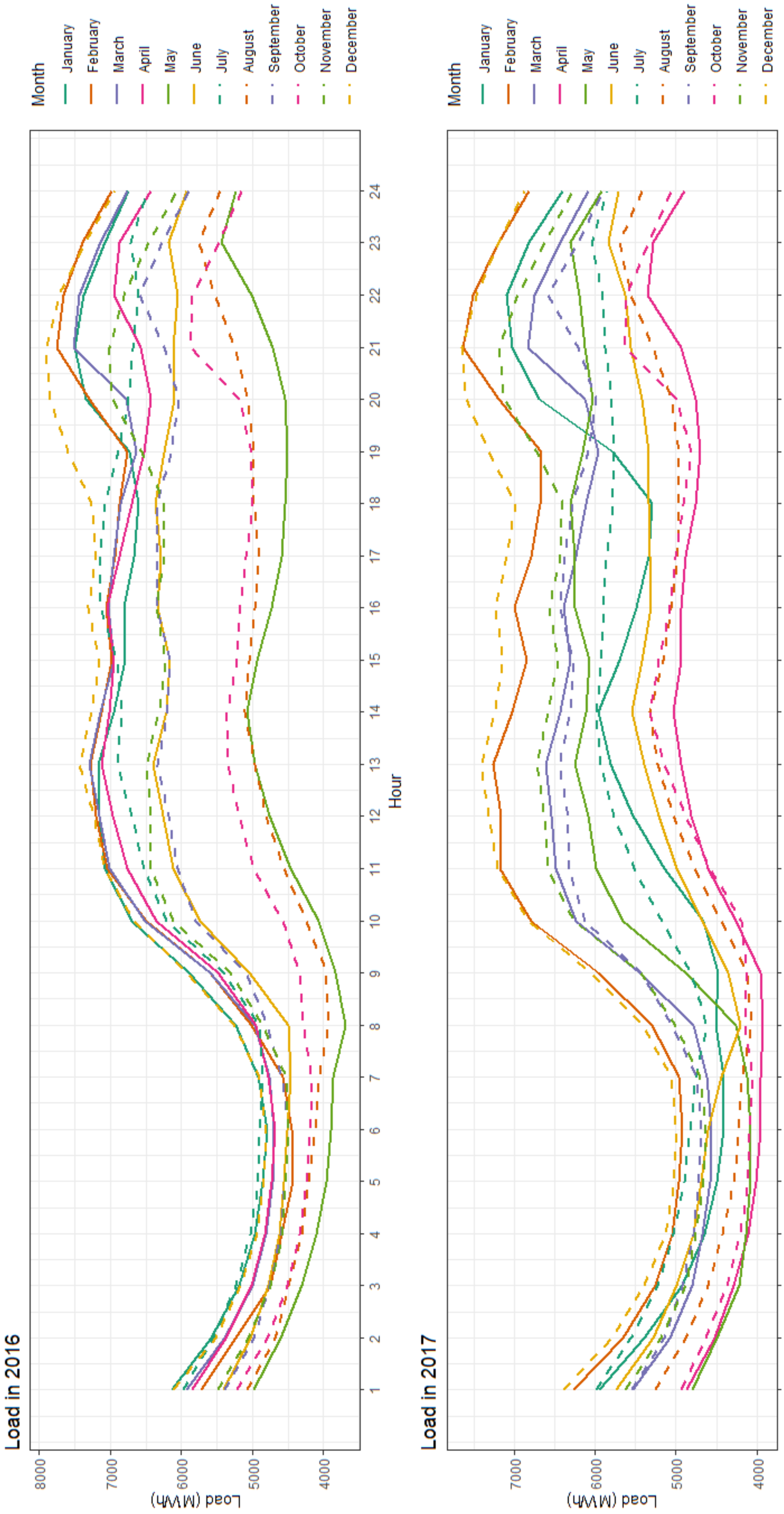

Figure 3.2: Historic load profiles for 2016 and 2017. Data source: REN (2018).

Chapter 4

Results and discussion

In this chapter, the results of the adopted model, described on the previous chapter, are highlighted. Firstly, the additional loads caused by the different EV penetration scenarios are presented and analysed. Secondly, the new MCPs (i.e. price increase due to the additional loads) are reported and discussed, for each EV penetration scenario. Finally, as previously stated, EV charging hours occurred between 17 h and 24 h and thus, both load increase results and new MCPs only apply to that specific time frame.

4.1 Load increase

Regarding the new loads obtained from additional demand caused by the different EV penetration scenarios, Table 4.1 on page 32 shows the mean values by month for the three different scenarios—S1, S2 and S3— for the considered years 2016 and 2017.

As previously stated, at the end of 2016, Portugal's electricity generation capacity was 19518 MWh. Taking this into account, it is observable that, even in the most extreme scenario S3, the demand caused by the EV fleet was lower than the total generation capacity.

A more detailed analysis of each year and scenarios is present in the following sections: first yearly load profiles and then month aggregated results for the same years.

Yearly load profiles

Results for 2016 showed that additional load is directly connected to the EV fleet size considered by each scenario, as expected. In Figure 4.1, the plotted graphics for scenarios 1 to 3 show an obvious difference in the additional charge faced by the grid when EVs are connected and charging. The additional load caused by the different EV fleets may differ in magnitude but their profile remains almost the same. This makes sense as the graphs in Figure 4.1 were generated from historic load observations to which a constant load by hour was added, as discussed in Chapter 3. To complement Figure 4.1, tables A.1, A.2 and A.3

on Annex A (page 45), show the summary statistics for each considered scenario in 2016. Hence, the main characteristics of each scenario's results are:

- Scenario 1 results show an average increment of 2.66% (+170.61 MWh) from the resulting additional EV load. The maximum value increased 5.40%, from 8160.79 MWh to 8626.46 MWh and the minimum load remained almost unchanged (+0.05%).
- Scenario 2, the average EV load increase accounted for 853.04 MWh (+12.02%). The maximum load was 10489.14 MWh (+22.20%) and the minimum was almost the same (+0.23%).
- Finally, scenario 3 presented the most extreme differences. The average load with EVs was 21.46% (+1706.08 MWh) higher than the average load without EVs (6243.82 MWh), the maximum 12817.48 MWh (+36.33%) and the minimum 4223.15 MWh (+0.45%).

Similarly to what happened in 2016, EV fleet size defined the additional load that the grid endured, plotted in Figure 4.2. Tables A.4 to A.6 (Annex A on page 46) show the summary statistics for the load results in 2017. Analysing the results:

- Scenario 1 average load increased 2.65% (+170.61 MWh). The maximum load increment was 5.06% and the minimum load increased only 1.24%.
- Scenario 2 registered higher load increases compared to scenario 1. Its average load value represented a 11.96% increase (+853.03 MWh), the maximum load increment reached 21.05% (+2233 MWh) and the minimum load increased 2.38%.
- At last, scenario 3 average load was 21.37% higher comparatively to the historic load mean, which corresponded to an average additional load of 1706.06 MWh. The minimum load increased 2.61% (+104.90 MWh) and the maximum load was 34.78% higher (+456.70 MWh).

Comparing the results obtained for 2016 and 2017, one can find that in both years, differences amongst scenarios followed the same pattern, especially when considering the yearly average values for load increase.

The range (difference between the lowest and highest values) is another important statistical tool to evaluate the differences in the loads between scenarios. These differences (maximum and minimum) are explained by the charging hour distribution (normal distribution), meaning that there is a higher charging density in peak hours (20 and 21 h) and fewer charging EVs in off-peak hours (remaining charging hours) (see tables in Annex A on pages 45–47).

Summing up, load increase is directly associated to EV fleet size and hence, there is an increasing load trend from scenario 1 to scenario 3. Peak hours registered the highest values and off-peak hours registered the lowest, as expected. Considering the different scenarios,there was enough installed capacity to respond to the EV inducted demand, theoretically.

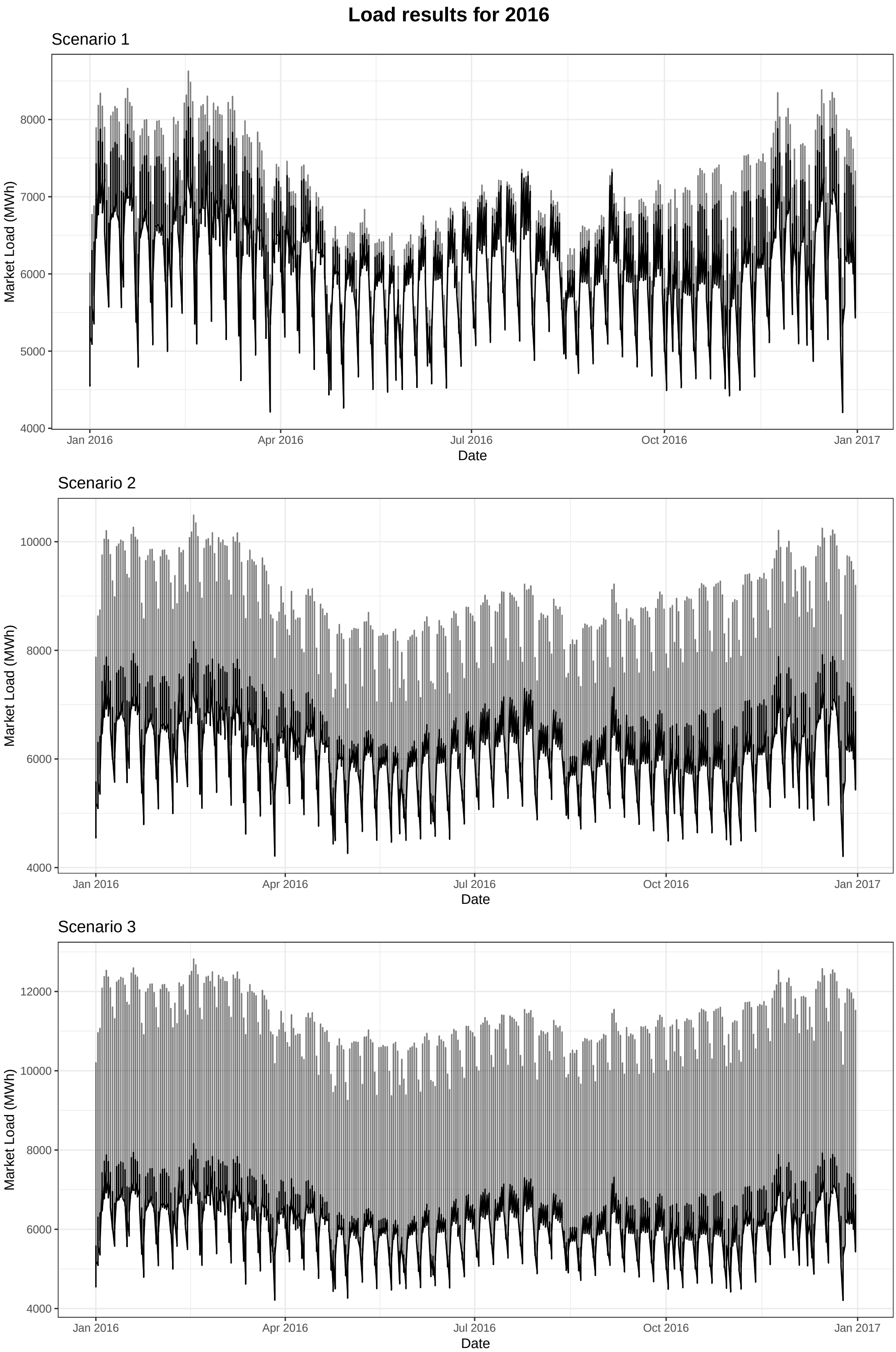

Figure 4.1: Yearly load diagrams for 2016 (selected hours 17–24h). In black, the historic load data and in grey the additional load caused by the different EV fleets (scenarios).

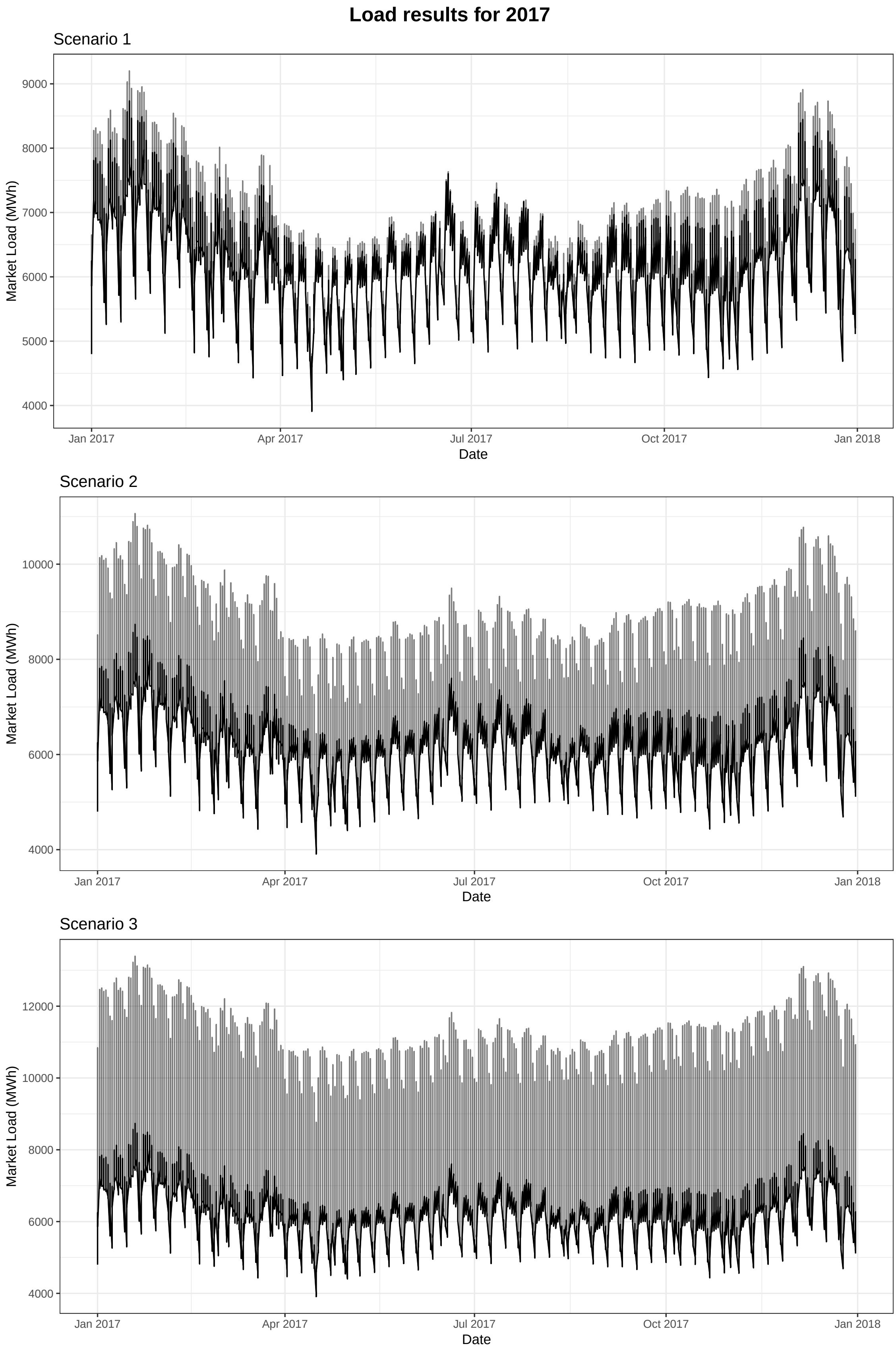

Figure 4.2: Yearly load diagrams for 2017 (selected hours 17–24h). In black, the historic load data and in grey the additional load caused by the different EV fleets (scenarios).

Monthly aggregated results

In terms of aggregated results, Table 4.1 shows that winter months (January, February, November and December) registered the highest loads for every considered scenario in 2016 and 2017. However, each month load growth was similar:

- *Scenario 1*—average monthly increase of 2.66% in 2016 and 2017.
- *Scenario 2*—average monthly increase of 12.02% in 2016 and 12.00% in 2017.
- *Scenario 3*—average monthly increase of 21.50% in 2016 and 21.43% in 2017.

The above results can be explained by the climacteric conditions that characterize the winter season. These months are generally colder and hence there is a higher demand for energy to warming purposes (households and workplaces, for example). As EV loads by month is virtually the same throughout the year (once again, this was due to the chosen charging behaviour), climacteric conditions are the main driver for the results obtained.

4.2 Price results

The results obtained from the simulation reinforced what was expected from the beginning: EV fleet size is the main driver to price increase. Regardless the year, the differences between the less extreme and most extreme scenarios (S1 and S3), is virtually the same.

However, a handful simulation results were not taken into consideration (in scenarios 2 and 3 in 2016 and scenario 3 in 2017) as these results' MCPs were lower than the historic MCPs (*new MCP* < *old MCP*). As demonstrated before (Chapter 3), in order to calculate the new MCPs, the adopted model recurred to available energy blocks (historic data from 2016 and 2017) and emulated the trading process until the additional demand, induced by the different EV fleets, was met. Nonetheless, in some hours (mainly in peak hours, i.e. 20h and 21h), there wasn't enough tradable blocks to meet the new demand needs—the algorithm summed all the available blocks to reach the new hourly MCP but, as listed extensively in Annex D (page 57), the shortage of available energy to supply the demand for those specific hours, the new MCP was not in line with what was expected. This means that for those specific hours, the demand was higher than the supply and hence it was infeasible to have that many EVs charging at those peak hours.

To be able to analyse and compare each scenario, the aforementioned results were discarded[1]. Bearing this in mind, a more detailed analysis for each scenario results is discussed ahead.

[1] If the results where the *new MCP* < *old MCP* were to be taken into consideration for statistical analysis, the average aggregated prices for more extreme penetration scenarios would have been lower than in less extreme scenarios (where there was enough energy to recalculate the new MCPs).

Table 4.1: Monthly load results (mean values) for 2016 and 2017.

Year 2016

		Scenario 1		Scenario 2		Scenario 3	
Month	**Market Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**
January	6742.94	170.55	6913.49	852.75	7595.69	1705.50	8448.44
February	6817.77	170.55	6988.32	852.75	7670.52	1705.50	8523.27
March	6510.81	171.23	6682.04	856.16	7366.97	1712.33	8223.14
April	6087.02	170.55	6257.57	852.75	6939.77	1705.50	7792.52
May	5722.35	170.55	5892.90	852.75	6575.10	1705.50	7427.85
June	5861.56	170.55	6032.11	852.75	6714.31	1705.50	7567.06
July	6284.71	170.55	6455.26	852.75	7137.46	1705.50	7990.21
August	5986.96	170.55	6157.51	852.75	6839.71	1705.50	7692.46
September	6121.58	170.55	6292.13	852.75	6974.33	1705.50	7827.08
October	5857.94	170.55	6028.49	852.75	6710.69	1705.50	7563.44
November	6382.92	170.55	6553.47	852.75	7235.67	1705.50	8088.42
December	6570.57	170.55	6741.12	852.75	7423.32	1705.50	8276.07

Year 2017

		Scenario 1		Scenario 2		Scenario 3	
Month	**Market Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**	**EV Load (MWh)**	**Total Load (MWh)**
January	7222.06	170.55	7392.61	852.75	8074.81	1705.50	8927.56
February	6675.37	170.55	6845.92	852.75	7528.12	1705.50	8380.87
March	6274.60	171.22	6445.82	856.09	7130.68	1712.17	7986.77
April	5634.44	170.55	5804.99	852.75	6487.19	1705.50	7339.94
May	5855.25	170.55	6025.80	852.75	6708.00	1705.50	7560.75
June	6151.43	170.55	6321.98	852.75	7004.18	1705.50	7856.93
July	6212.13	170.55	6382.68	852.75	7064.88	1705.50	7917.63
August	5968.93	170.55	6139.48	852.75	6821.68	1705.50	7674.43
September	6106.36	170.55	6276.91	852.75	6959.11	1705.50	7811.86
October	6007.76	170.55	6178.31	852.75	6860.51	1705.50	7713.26
November	6332.51	170.55	6503.06	852.75	7185.26	1705.50	8038.01
December	6898.68	170.55	7069.23	852.75	7751.43	1705.50	8604.18

Results for 2016

The obtained results for 2016 that only the first scenario, 1% EV penetration, were feasible to the available offered energy in the wholesale market. Scenarios 2 and 3 (5 and 10% EV penetration) presented many hours (peak hours) where there wasn't enough energy to meet demand. The tables with the detailed information for aggregated results by month are listed in Annex C.

The annual average MCP for scenario 1 represented a 5.59% increase in price (+2.47 €/MWh). Winter months (January, February, and March) contributed with the highest increments. However, December was an exception to the trend (represented only a 2.92% increase) (see Figure 4.3 and Table C.1). Nonetheless, every month showed higher prices when compared to a scenario where no EVs were charging.

On the same terms, scenario 2 (5% penetration scenario) annual average accounted for a 25.66% rise (+14.35 €/MWh). Once again, winter months were the ones with the highest growth (Table C.2).

Finally, scenario 3 presented the highest price increases. The average annual MCP grew amost 40% (+26.88 €/MWh). Monthly average results are more even, although this does not correspond to what should have been obtained. In fact and as said before, 346 results were not taken into consideration. These infeasible results took place throughout the entire year (with higher concentration in winter months) and thus, the proportionality of price increase is not accurate (see tables D.1 and D.2 where every infeasible result is listed).

Results for 2017

Contrary to what happened in 2016, the first two scenario results for 2017 are more feasible. Since 2017 was a year with increased energy production, there was enough energy to meet the additional demand of the EV fleets for scenario 1 and 2.

The annual average increase for scenario 1 was +4.23% (2.41€/MWh). Monthly average increases were somewhat constant (low variance between months), as seen in Table C.4.

For scenario 2, more drastic price increases were obtained. The annual average increase was 14.83% (+9.49€/MWh) and winter months registered higher increments than summer ("warmer") months.

Finally, scenario 3 annual MCP accounted for a 30.50% rise price-wise. Similarly to scenario 3 in 2016, the number of infeasible results is somewhat high (110). In this scenario, the price growth difference between summer and winter months is inaccurate, as the majority of the "errors" occurred in winter months (Table D.3).

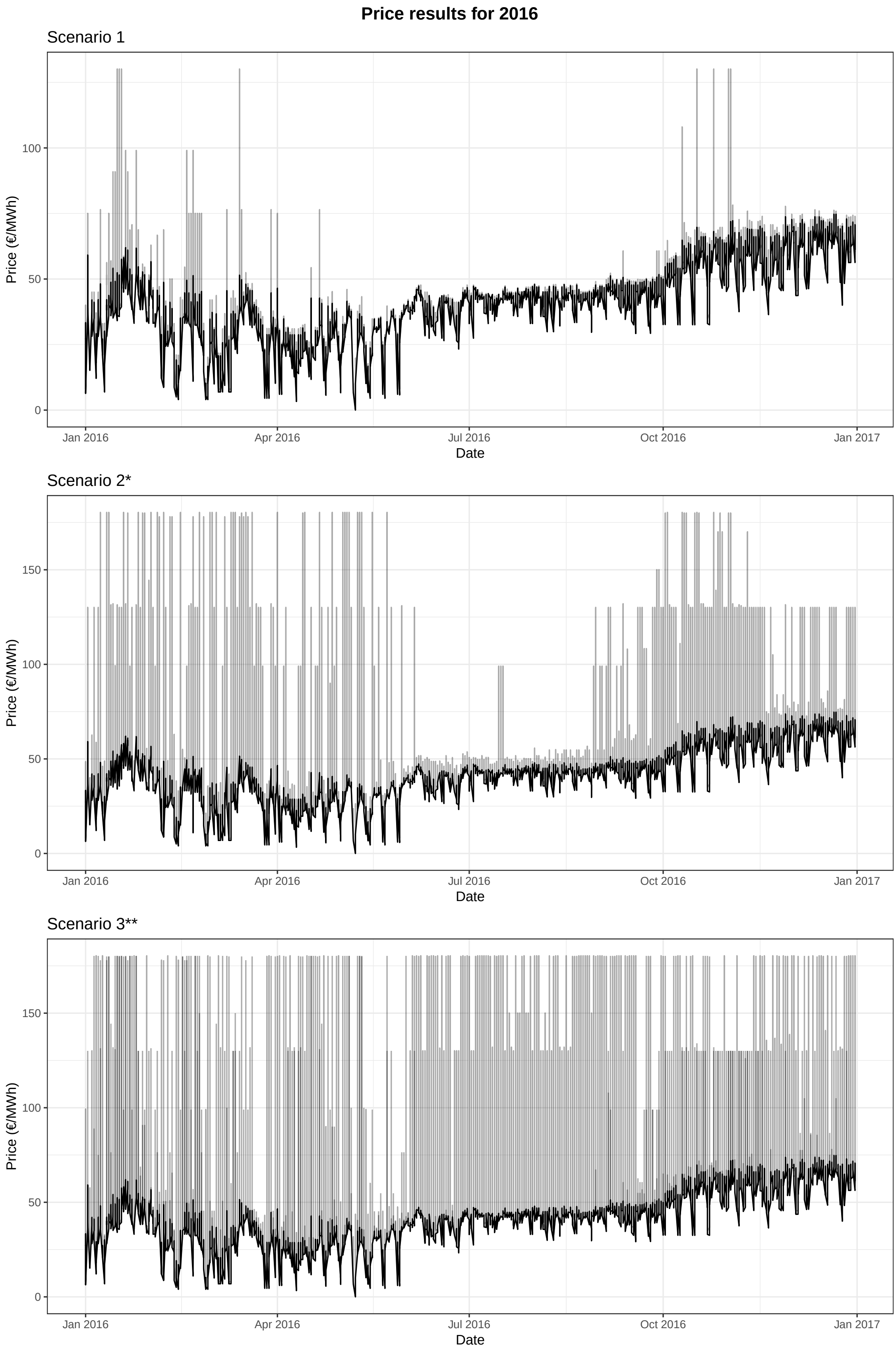

Figure 4.3: Simulation results for 2016: in black are represented the historic MCPs (*old MCP*) and in grey the *new MCP* (price increase) for each day of 2016. (*)Scenario 2 plot omits 48 results. (**)Scenario 3 plot omits 346 results. These omitted results are due to the fact that the *new MCP* < *old MCP*.

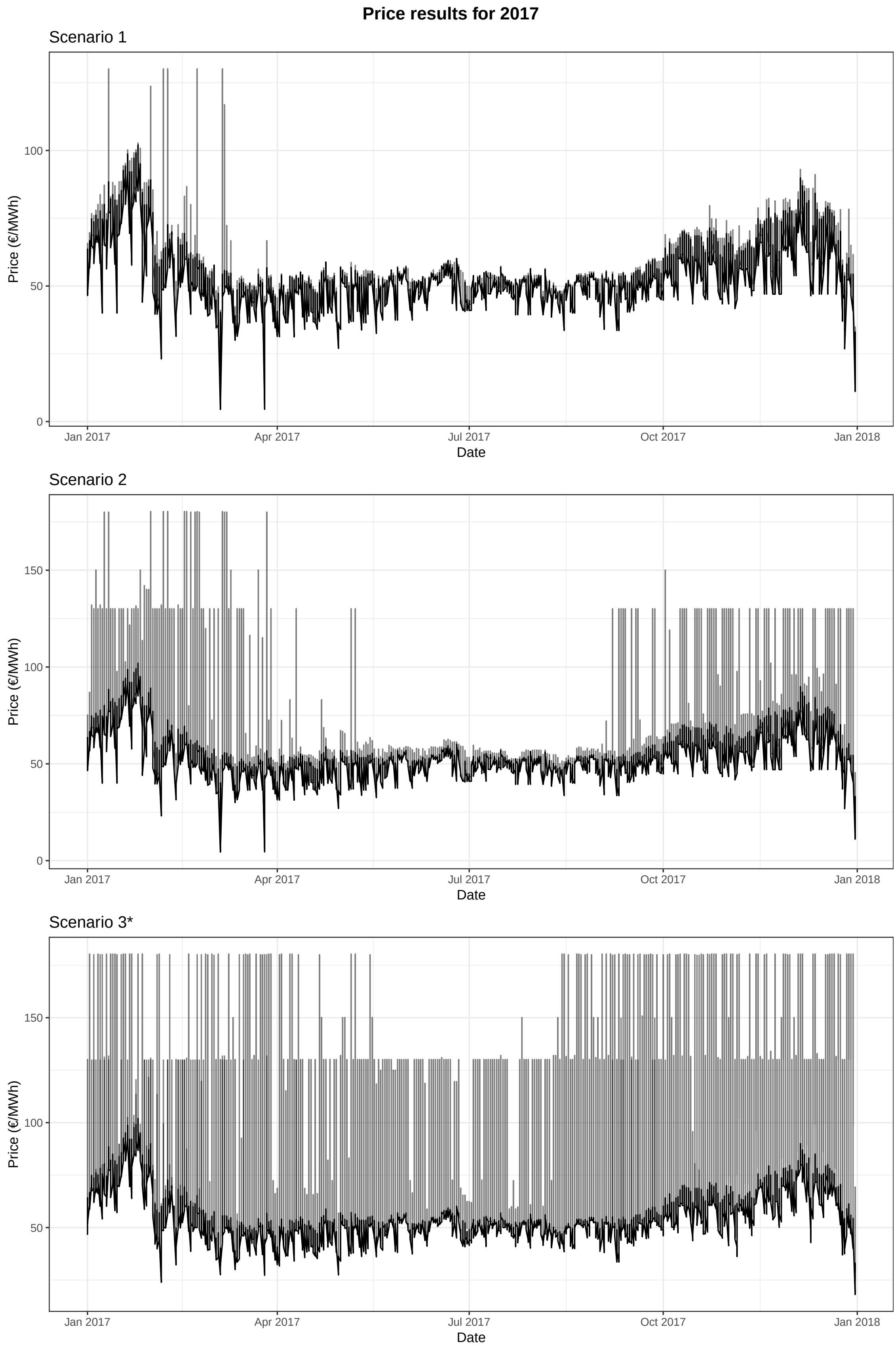

Figure 4.4: Price results for 2017: in black are represented the historic MCPs (*old MCP*) and in grey the *new MCP* (price increase) for each day of 2017. (*)Scenario 3 plot has 110 omitted results. These omitted results are due to the fact that the *new MCP* < *old MCP*.

Chapter 5

Conclusions and final remarks

At the present time, only small EV fleets can be integrated in the Portuguese grid without major impacts.After a thorough analysis of the simulation results, the main drawn conclusion was that the Portuguese electric grid is not capable of enduring EV fleets of the sizes of the ones tested in this thesis as scenario 2 and 3.

It is not a problem of grid infrastructure nor total installed capacity. As seen, the grid has enough installed capacity to endure the different EV fleets. However, the main reason to price increase was related to market operation issues.

EV influence on market operation

As previously seen, depending on the number of EVs charging, electricity prices can increase up to 40% in the most extreme scenario. In operational terms, market participants and all the other stakeholders must be prepared to the increasing EV penetration that is going to take place in the near future.

In scenarios where EV penetration rates were medium to high (i.e. scenarios 2 and 3), the electricity wholesale market was not prepared for the additional load. In simpler terms, there wasn't enough energy to supply, mainly at peak hours. This is the main conclusion of this work: market agents, and in these case producers, have to be aware that in peak hours the market failed to deliver enough energy.

A possible solution to the lack of electricity supply in peak hours could be integrating RES to manage and shape price increase and "regulate" charging behaviours through charging tariffs (as some authors defend, as exposed in Chapter 2).

It was not possible to infer to what degree did RES influence the final price increase when comparing the results between 2016 and 2017. The average annual prices were similar for both years.

Research limitations and future perspectives

The main research limitations of this work were (i) the time frame defined for EV charging, (ii) driver behaviour, (iii) CO_2 emissions related to the additional energy generation to meet additional load demand and (iv) the fact that only the Portuguese wholesale market was assessed:

- The time frame defined was chosen to test if the grid was capable of enduring additional loads in peak hours, but it is very limited because EV drivers are not going to charge their vehicles only at those specific hours, but through the entire day.
- Driver behaviour is important to determine each EV SoC and ultimately its charging needs, i.e. how much energy will be needed to charge the EV.
- CO_2 associated emissions were not measured. This is important in order to know the EV carbon footprint and complete a well-to-wheels analysis.
- Finally, only assessing the potential impacts of EVs on the Portuguese wholesale market, represented the biggest limitation of this work. However, considering a scenario where interconnection (and hence energy importation) between Portugal and Spain was not possible, it can prove useful to understand what would occur in the Portuguese wholesale market alone.

In conclusion, future works on the impacts of EVs on the electricity systems should focus on bringing together the many dimensions of sustainable development—social-economic, environmental and in this specific case, technical analysis. Moreover, within the intention of creating a single European wholesale market, it is important to develop works that analyse what would happen to electricity markets across Europe, bearing in mind that transmission infrastructure has yet to be built.

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Annexes

Annex A

Load summary statistics

Table A.1: Summary statistics for Scenario 1 results in 2016.

Scenario 1 (2016)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6243.82	Mean	6414.43	Mean	2.66%
Standard Error	13.34	Standard Error	14.16	Standard Error	5.84%
Median	6283.83	Median	6448.73	Median	2.56%
Standard Deviation	721.49	Standard Deviation	766.22	Standard Deviation	5.84%
Sample Variance	520548.92	Sample Variance	587093.03	Sample Variance	11.33%
Kurtosis	-0.24	Kurtosis	-0.09	Kurtosis	-170.32%
Skewness	-0.24	Skewness	-0.10	Skewness	-145.24%
Range	3956.73	Range	4420.49	Range	10.49%
Minimum	4204.05	Minimum	4205.96	Minimum	0.05%
Maximum	8160.79	Maximum	8626.46	Maximum	5.40%
Sample size (N)	2927	Sample size (N)	2927	Sample size (N)	0.00%

Table A.2: Summary statistics for Scenario 2 results in 2016.

Scenario 2 (2016)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6243.82	Mean	7096.86	Mean	12.02%
Standard Error	13.34	Standard Error	22.88	Standard Error	41.71%
Median	6283.83	Median	6926.57	Median	9.28%
Standard Deviation	721.49	Standard Deviation	1237.83	Standard Deviation	41.71%
Sample Variance	520548.92	Sample Variance	1532221.75	Sample Variance	66.03%
Kurtosis	-0.24	Kurtosis	-0.38	Kurtosis	37.82%
Skewness	-0.24	Skewness	0.40	Skewness	160.29%
Range	3956.73	Range	6275.53	Range	36.95%
Minimum	4204.05	Minimum	4213.60	Minimum	0.23%
Maximum	8160.79	Maximum	10489.14	Maximum	22.20%
Sample size (N)	2927	Sample size (N)	2927	Sample size (N)	0.00%

Table A.3: Summary statistics for Scenario 3 results in 2016.

Scenario 3 (2016)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6243.82	Mean	7949.90	Mean	21.46%
Standard Error	13.34	Standard Error	38.07	Standard Error	64.97%
Median	6283.83	Median	7282.91	Median	13.72%
Standard Deviation	721.49	Standard Deviation	2059.44	Standard Deviation	64.97%
Sample Variance	520548.92	Sample Variance	4241275.21	Sample Variance	87.73%
Kurtosis	-0.24	Kurtosis	-0.81	Kurtosis	70.68%
Skewness	-0.24	Skewness	0.60	Skewness	140.78%
Range	3956.73	Range	8594.33	Range	53.96%
Minimum	4204.05	Minimum	4223.15	Minimum	0.45%
Maximum	8160.79	Maximum	12817.48	Maximum	36.33%
Sample size (N)	2927	Sample size (N)	2927	Sample size (N)	0.00%

Table A.4: Summary statistics for Scenario 1 results in 2017.

Scenario 1 (2017)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6277.47	Mean	6448.07	Mean	2.65%
Standard Error	14.36	Standard Error	15.15	Standard Error	5.21%
Median	6286.14	Median	6438.95	Median	2.37%
Standard Deviation	775.68	Standard Deviation	818.29	Standard Deviation	5.21%
Sample Variance	601673.40	Sample Variance	669603.39	Sample Variance	10.14%
Kurtosis	0.05	Kurtosis	0.20	Kurtosis	77.13%
Skewness	0.07	Skewness	0.18	Skewness	61.02%
Range	4824.61	Range	5241.00	Range	7.94%
Minimum	3909.36	Minimum	3958.64	Minimum	1.24%
Maximum	8733.97	Maximum	9199.64	Maximum	5.06%
Count	2919	Count	2919	Count	0

Table A.5: Summary statistics for Scenario 2 results in 2017.

Scenario 2 (2017)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6277.47	Mean	7130.50	Mean	11.96%
Standard Error	14.36	Standard Error	23.56	Standard Error	39.06%
Median	6286.14	Median	6958.76	Median	9.67%
Standard Deviation	775.68	Standard Deviation	1272.90	Standard Deviation	39.06%
Sample Variance	601673.40	Sample Variance	1620285.26	Sample Variance	62.87%
Kurtosis	0.05	Kurtosis	-0.20	Kurtosis	122.98%
Skewness	0.07	Skewness	0.49	Skewness	85.16%
Range	4824.61	Range	7057.61	Range	31.64%
Minimum	3909.36	Minimum	4004.71	Minimum	2.38%
Maximum	8733.97	Maximum	11062.32	Maximum	21.05%
Count	2919	Count	2919	Count	0

Table A.6: Summary statistics for Scenario 3 results in 2017.

Scenario 3 (2017)					
Market Load		**Total Load**		**Percentage Change**	
Mean	6277.47	Mean	7983.53	Mean	21.37%
Standard Error	14.36	Standard Error	38.54	Standard Error	62.75%
Median	6286.14	Median	7348.73	Median	14.46%
Standard Deviation	775.68	Standard Deviation	2082.38	Standard Deviation	62.75%
Sample Variance	601673.40	Sample Variance	4336301.82	Sample Variance	86.12%
Kurtosis	0.05	Kurtosis	-0.73	Kurtosis	106.27%
Skewness	0.07	Skewness	0.62	Skewness	88.34%
Range	4824.61	Range	9376.41	Range	48.55%
Minimum	3909.36	Minimum	4014.26	Minimum	2.61%
Maximum	8733.97	Maximum	13390.67	Maximum	34.78%
Count	2919	Count	2919	Count	0

Annex B

Price summary statistics

Table B.1: Summary statistics for scenario 1 in 2016.

Scenario 1 (2016)					
New Price		**Old Price**		**Variation**	
Mean	44.13	Mean	41.66	Mean	5.59%
Standard Error	0.31	Standard Error	0.28	Standard Error	9.47%
Median	43.60	Median	41.98	Median	3.72%
Standard Deviation	16.74	Standard Deviation	15.15	Standard Deviation	9.47%
Sample Variance	280.09	Sample Variance	229.56	Sample Variance	18.04%
Kurtosis	1.95	Kurtosis	-0.14	Kurtosis	107.25%
Skewness	0.49	Skewness	-0.10	Skewness	120.18%
Range	129.97	Range	74.69	Range	42.53%
Minimum	0.10	Minimum	0.00	Minimum	100.00%
Maximum	130.07	Maximum	74.69	Maximum	42.58%
Sample size (N)	2927	Sample size (N)	2927	Sample size (N)	0.00%

Table B.2: Summary statistics for scenario 2 in 2016.

Scenario 2 (2016)					
New Price		**Old Price**		**Variation**	
Mean	55.92	Mean	41.57	Mean	25.66%
Standard Error	0.65	Standard Error	0.28	Standard Error	56.60%
Median	46.46	Median	41.79	Median	10.05%
Standard Deviation	35.10	Standard Deviation	15.23	Standard Deviation	56.60%
Sample Variance	1231.78	Sample Variance	231.99	Sample Variance	81.17%
Kurtosis	3.53	Kurtosis	-0.16	Kurtosis	104.64%
Skewness	1.87	Skewness	-0.09	Skewness	104.57%
Range	180.20	Range	74.69	Range	58.55%
Minimum	0.10	Minimum	0.00	Minimum	100.00%
Maximum	180.30	Maximum	74.69	Maximum	58.57%
Sample size (N)	2879	Sample size (N)	2879	Sample size (N)	0.00%

Table B.3: Summary statistics for scenario 3 in 2016.

Scenario 3 (2016)					
New Price		**Old Price**		**Variation**	
Mean	67.89	Mean	41.00	Mean	39.60%
Standard Error	0.97	Standard Error	0.30	Standard Error	69.23%
Median	47.69	Median	41.70	Median	12.56%
Standard Deviation	49.36	Standard Deviation	15.19	Standard Deviation	69.23%
Sample Variance	2436.76	Sample Variance	230.71	Sample Variance	90.53%
Kurtosis	0.48	Kurtosis	-0.12	Kurtosis	125.77%
Skewness	1.33	Skewness	-0.13	Skewness	109.52%
Range	180.20	Range	74.69	Range	58.55%
Minimum	0.10	Minimum	0.00	Minimum	100.00%
Maximum	180.30	Maximum	74.69	Maximum	58.57%
Sample size (N)	2581	Sample size (N)	2581	Sample size (N)	0.00%

Table B.4: Summary statistics for scenario 1 in 2017.

Scenario 1 (2017)					
New Price		**Old Price**		**Variation**	
Mean	56.91	Mean	54.50	Mean	4.23%
Standard Error	0.24	Standard Error	0.23	Standard Error	5.78%
Median	53.21	Median	51.95	Median	2.37%
Standard Deviation	13.14	Standard Deviation	12.38	Standard Deviation	5.78%
Sample Variance	172.61	Sample Variance	153.24	Sample Variance	11.22%
Kurtosis	3.31	Kurtosis	1.52	Kurtosis	54.15%
Skewness	1.22	Skewness	0.78	Skewness	36.30%
Range	124.07	Range	97.49	Range	21.42%
Minimum	6.00	Minimum	4.50	Minimum	25.00%
Maximum	130.07	Maximum	101.99	Maximum	21.59%
Count	2919	Count	2919	Count	0.00%

Table B.5: Summary statistics for scenario 2 in 2017.

Scenario 2 (2017)					
New Price		**Old Price**		**Variation**	
Mean	63.99	Mean	54.50	Mean	14.83%
Standard Error	0.46	Standard Error	0.23	Standard Error	49.84%
Median	55.55	Median	51.95	Median	6.48%
Standard Deviation	24.68	Standard Deviation	12.38	Standard Deviation	49.84%
Sample Variance	609.11	Sample Variance	153.24	Sample Variance	74.84%
Kurtosis	5.14	Kurtosis	1.52	Kurtosis	70.45%
Skewness	2.18	Skewness	0.78	Skewness	64.35%
Range	174.30	Range	97.49	Range	44.07%
Minimum	6.00	Minimum	4.50	Minimum	25.00%
Maximum	180.30	Maximum	101.99	Maximum	43.43%
Count	2919	Count	2919	Count	0.00%

Table B.6: Summary statistics for scenario 3 in 2017.

Scenario 3 (2017)					
New Price		**Old Price**		**Variation**	
Mean	77.71	Mean	54.01	Mean	30.50%
Standard Error	0.75	Standard Error	0.23	Standard Error	69.70%
Median	58.85	Median	51.69	Median	12.17%
Standard Deviation	39.87	Standard Deviation	12.08	Standard Deviation	69.70%
Sample Variance	1589.67	Sample Variance	145.99	Sample Variance	90.82%
Kurtosis	0.60	Kurtosis	1.62	Kurtosis	-169.34%
Skewness	1.33	Skewness	0.76	Skewness	42.75%
Range	174.30	Range	97.49	Range	44.07%
Minimum	6.00	Minimum	4.50	Minimum	25.00%
Maximum	180.30	Maximum	101.99	Maximum	43.43%
Count	2809	Count	2809	Count	0.00%

Annex C

Simulation results

In this Annex, the average price results, aggregated by month for each considered year, is presented. Some of the tables are marked with an asterisk (*), which means that those tables are missing some of the results. This was due to insufficient offer bids to match the demand for the specified hour. These cases are described extensively on Annex D (Tables D.1 to D.3).

Table C.1: Price simulation results for Scenario 1 in 2016 (average prices).

Scenario 1 (N = 2927)				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	46.62	41.02	5.60	12.01%
February	34.80	30.54	4.26	12.24%
March	32.30	29.58	2.71	8.40%
April	26.63	24.80	1.83	6.88%
May	27.66	26.19	1.47	5.31%
June	39.97	38.07	1.90	4.75%
July	43.24	41.65	1.59	3.68%
August	43.41	41.88	1.53	3.53%
September	46.08	44.69	1.39	3.01%
October	57.58	55.18	2.40	4.18%
November	63.84	60.81	3.03	4.75%
December	66.79	64.84	1.95	2.92%
Annual	**44.13**	**41.66**	**2.47**	**5.59%**

Table C.2: Price simulation results for Scenario 2 in 2016 (average prices).

Scenario 2 (N = 2879)*				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	62.00	39.97	22.03	35.53%
February	50.04	29.43	20.61	41.18%
March	49.46	29.13	20.33	41.11%
April	40.11	24.66	15.45	38.52%
May	44.64	26.12	18.52	41.49%
June	43.02	38.07	4.95	11.50%
July	46.36	41.65	4.71	10.16%
August	46.50	41.88	4.61	9.92%
September	57.50	44.69	12.81	22.28%
October	77.02	55.18	21.84	28.36%
November	77.20	60.81	16.39	21.23%
December	76.19	64.84	11.35	14.89%
Annual	**55.92**	**41.57**	**14.35**	**25.66%**
* Ommited results (N = 48)				

Table C.3: Price simulation results for Scenario 3 in 2016 (average prices).

Scenario 3 (N = 2581)*				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	70.44	38.89	31.54	44.78%
February	54.84	27.80	27.03	49.30%
March	45.23	27.34	17.89	39.54%
April	51.77	23.91	27.85	53.80%
May	41.39	24.74	16.65	40.22%
June	69.32	38.02	31.29	45.15%
July	74.78	41.65	33.14	44.31%
August	74.53	41.86	32.67	43.83%
September	73.48	44.24	29.24	39.80%
October	76.58	53.78	22.80	29.77%
November	84.89	59.87	25.02	29.48%
December	88.63	64.34	24.29	27.40%
Annual	**67.89**	**41.00**	**26.88**	**39.60%**
*Ommited results (N = 346)				

Table C.4: Price simulation results for Scenario 1 in 2017 (average prices).

Scenario 1 (N = 2919)				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	79.89	77.40	2.49	3.12%
February	58.84	55.29	3.55	6.03%
March	47.60	45.26	2.34	4.91%
April	46.71	44.58	2.13	4.55%
May	50.14	48.04	2.10	4.18%
June	52.44	50.26	2.17	4.15%
July	51.10	49.09	2.01	3.93%
August	50.11	48.77	1.34	2.68%
September	51.07	49.44	1.63	3.19%
October	61.08	58.76	2.32	3.80%
November	65.96	62.78	3.17	4.81%
December	67.83	64.01	3.82	5.63%
Annual	**56.91**	**54.50**	**2.41**	**4.23%**

Table C.5: Price simulation results for Scenario 2 in 2017 (average prices).

Scenario 2 (N = 2919)				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	91.31	77.40	13.91	15.23%
February	76.18	55.40	20.78	27.28%
March	59.55	45.30	14.25	23.93%
April	49.73	44.57	5.16	10.38%
May	52.99	47.95	5.03	9.50%
June	54.36	50.33	4.03	7.42%
July	52.47	49.05	3.43	6.53%
August	51.80	48.79	3.02	5.82%
September	57.17	49.43	7.73	13.53%
October	70.89	58.78	12.10	17.08%
November	74.37	62.72	11.65	15.67%
December	77.57	64.00	13.57	17.50%
Annual	**63.99**	**54.50**	**9.49**	**14.83%**

Table C.6: Price simulation results for Scenario 3 in 2017 (average prices).

Scenario 3 (N = 2809)*				
Month	**Price results (€/MWh)**		**Price increase**	
	New MCP	Old MCP	€/MWh	%
January	98.44	76.38	22.06	22.41%
February	73.56	53.53	20.03	27.23%
March	69.38	44.68	24.70	35.61%
April	65.85	44.54	21.31	32.37%
May	71.10	47.95	23.15	32.56%
June	67.78	50.33	17.46	25.75%
July	66.42	49.05	17.38	26.16%
August	73.25	48.79	24.46	33.39%
September	78.35	49.24	29.11	37.15%
October	86.56	58.53	28.03	32.38%
November	89.91	62.65	27.26	30.32%
December	92.68	63.97	28.71	30.98%
Annual	**77.71**	**54.01**	**23.70**	**30.50%**
*Ommited results (N = 110)				

Annex D

Infeasible results

The following tables list the results obtained from the simulation model. The results in bold are the ones in which there wasn't enough bid offers to meet additional demand ate each specific hour (infeasible results).

D.1 Results for 2016

Table D.1: Infeasible results for scenario 2 in 2016.

Day	Hour	New Price (€/MWh)	Old Price (€/MWh)
14/01/2016	20	**0.00**	49.10
14/01/2016	21	**0.00**	46.60
15/01/2016	20	**0.00**	49.10
15/01/2016	21	**0.00**	45.89
16/01/2016	20	**0.00**	52.38
16/01/2016	21	**0.00**	46.60
17/01/2016	20	**0.00**	51.51
17/01/2016	21	**0.00**	45.89
18/01/2016	20	**0.00**	57.50
18/01/2016	21	**0.00**	54.57
20/01/2016	20	**0.00**	61.94
20/01/2016	21	**0.00**	61.94
21/01/2016	20	**0.00**	61.01
22/01/2016	20	**0.00**	53.79
22/01/2016	21	**0.00**	53.60
23/01/2016	20	**0.00**	51.60

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Table D.1 – *Continued from previous page*

23/01/2016	21	**0.00**	51.60
25/01/2016	20	**0.00**	61.73
25/01/2016	21	**0.00**	61.73
16/02/2016	20	**0.00**	35.10
16/02/2016	21	**0.00**	35.10
17/02/2016	20	**0.00**	44.69
17/02/2016	21	**0.00**	44.69
18/02/2016	20	**0.00**	49.50
18/02/2016	21	**0.00**	44.69
19/02/2016	20	**0.00**	44.69
19/02/2016	21	**0.00**	44.69
20/02/2016	20	**0.00**	41.25
20/02/2016	21	**0.00**	41.25
21/02/2016	20	**0.00**	41.25
21/02/2016	21	**0.00**	50.50
22/02/2016	20	**0.00**	44.05
22/02/2016	21	**0.00**	44.40
23/02/2016	20	**0.00**	41.25
23/02/2016	21	**0.00**	41.25
24/02/2016	20	**0.00**	44.19
25/02/2016	20	**0.00**	45.19
25/02/2016	21	**0.00**	39.69
08/03/2016	20	**0.00**	45.50
08/03/2016	21	**0.00**	45.50
14/03/2016	20	**0.00**	50.89
14/03/2016	21	**0.00**	51.40
15/03/2016	21	**0.00**	49.69
29/03/2016	21	**0.00**	44.69
01/04/2016	21	**0.00**	40.09
21/04/2016	21	**0.00**	41.69
04/05/2016	21	**0.00**	36.15
11/05/2016	21	**0.00**	34.69

Table D.2: Infeasible results for scenario 3 in 2016.

Day	Hour	New Price (€/MWh)	Old Price (€/MWh)
02/01/2016	20	**0.00**	55.10
02/01/2016	21	**0.10**	58.58
05/01/2016	20	**0.00**	41.10
07/01/2016	20	**0.00**	42.10
08/01/2016	20	**1.00**	48.10
08/01/2016	21	**1.00**	48.10
10/01/2016	20	**0.00**	30.10
10/01/2016	21	**0.00**	30.10
11/01/2016	20	**1.00**	38.10
11/01/2016	21	**4.00**	40.10
12/01/2016	20	**0.10**	43.69
12/01/2016	21	**0.10**	43.69
13/01/2016	20	**0.00**	48.76
13/01/2016	21	**0.00**	40.10
14/01/2016	19	**0.00**	54.10
14/01/2016	20	**1.00**	49.10
14/01/2016	21	**1.00**	46.60
15/01/2016	20	**1.00**	49.10
15/01/2016	21	**1.00**	45.89
16/01/2016	20	**1.01**	52.38
16/01/2016	21	**1.00**	46.60
17/01/2016	20	**1.00**	51.51
17/01/2016	21	**1.00**	45.89
18/01/2016	20	**4.00**	57.50
18/01/2016	21	**1.00**	54.57
19/01/2016	20	**1.00**	53.85
19/01/2016	21	**0.00**	52.67
20/01/2016	20	**4.00**	61.94
20/01/2016	21	**4.00**	61.94
21/01/2016	20	**1.00**	61.01
21/01/2016	21	**0.10**	60.01
22/01/2016	20	**1.00**	53.79
22/01/2016	21	**1.00**	53.60

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Table D.2 – *Continued from previous page*

23/01/2016	20	**1.00**	51.60
23/01/2016	21	**1.00**	51.60
25/01/2016	20	**1.00**	61.73
25/01/2016	21	**1.00**	61.73
26/01/2016	20	**1.00**	54.62
26/01/2016	21	**1.00**	54.40
27/01/2016	20	**0.00**	48.10
27/01/2016	21	**0.00**	49.49
28/01/2016	20	**0.10**	52.69
28/01/2016	21	**0.00**	51.62
29/01/2016	20	**0.00**	51.60
29/01/2016	21	**0.00**	51.10
31/01/2016	20	**0.00**	45.69
31/01/2016	21	**0.00**	48.95
01/02/2016	20	**1.00**	55.55
01/02/2016	21	**1.00**	56.55
02/02/2016	20	**0.00**	45.69
02/02/2016	21	**0.00**	45.69
03/02/2016	20	**0.00**	36.19
03/02/2016	21	**0.00**	36.19
04/02/2016	20	**1.00**	45.69
04/02/2016	21	**0.00**	42.90
05/02/2016	20	**0.10**	43.69
05/02/2016	21	**0.00**	43.53
07/02/2016	21	**1.00**	48.69
08/02/2016	20	**0.00**	37.69
08/02/2016	21	**0.00**	39.69
10/02/2016	20	**0.10**	41.10
10/02/2016	21	**0.00**	37.69
11/02/2016	20	**0.00**	38.69
11/02/2016	21	**0.00**	37.19
12/02/2016	20	**0.00**	29.60
12/02/2016	21	**0.00**	29.60
15/02/2016	20	**0.00**	35.10
15/02/2016	21	**0.00**	35.10

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Table D.2 – *Continued from previous page*

16/02/2016	20	**0.00**	35.10
16/02/2016	21	**0.00**	35.10
17/02/2016	20	**0.00**	44.69
17/02/2016	21	**0.00**	44.69
18/02/2016	20	**4.00**	49.50
18/02/2016	21	**0.55**	44.69
19/02/2016	20	**0.10**	44.69
19/02/2016	21	**4.00**	44.69
19/02/2016	22	**0.00**	44.69
20/02/2016	20	**4.00**	41.25
20/02/2016	21	**4.00**	41.25
21/02/2016	20	**4.00**	41.25
21/02/2016	21	**4.00**	50.50
21/02/2016	22	**0.00**	51.25
22/02/2016	20	**4.00**	44.05
22/02/2016	21	**4.00**	44.40
23/02/2016	20	**5.00**	41.25
23/02/2016	21	**5.00**	41.25
24/02/2016	20	**5.00**	44.19
24/02/2016	21	**4.00**	37.50
25/02/2016	20	**5.00**	45.19
25/02/2016	21	**5.00**	39.69
26/02/2016	20	**0.00**	30.21
26/02/2016	21	**0.00**	30.21
29/02/2016	20	**4.00**	34.69
29/02/2016	21	**4.00**	34.69
01/03/2016	20	**0.10**	37.24
01/03/2016	21	**0.10**	37.24
02/03/2016	20	**0.00**	30.69
02/03/2016	21	**0.00**	30.69
03/03/2016	20	**4.00**	36.69
03/03/2016	21	**4.00**	36.69
05/03/2016	21	**0.00**	19.69
06/03/2016	21	**0.00**	25.69
07/03/2016	20	**0.00**	28.69

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Table D.2 – *Continued from previous page*

07/03/2016	21	**0.00**	32.00
08/03/2016	20	**4.50**	45.50
08/03/2016	21	**4.50**	45.50
09/03/2016	21	**0.00**	26.69
10/03/2016	20	**0.00**	29.20
10/03/2016	21	**4.00**	36.69
11/03/2016	20	**0.10**	35.69
11/03/2016	21	**4.00**	37.69
12/03/2016	20	**4.50**	36.69
12/03/2016	21	**4.00**	34.33
13/03/2016	20	**0.10**	33.33
13/03/2016	21	**0.00**	34.33
14/03/2016	20	**10.00**	50.89
14/03/2016	21	**10.00**	51.40
14/03/2016	22	**0.00**	51.40
15/03/2016	20	**4.00**	44.40
15/03/2016	21	**8.00**	49.69
16/03/2016	20	**0.00**	41.16
16/03/2016	21	**0.10**	43.40
17/03/2016	20	**4.00**	46.69
17/03/2016	21	**4.50**	48.01
18/03/2016	20	**0.00**	43.05
18/03/2016	21	**0.10**	46.69
19/03/2016	20	**0.00**	41.10
19/03/2016	21	**0.00**	44.60
20/03/2016	20	**0.00**	41.69
20/03/2016	21	**4.00**	45.60
21/03/2016	20	**0.00**	40.20
21/03/2016	21	**0.00**	40.05
22/03/2016	20	**0.10**	39.46
22/03/2016	21	**0.00**	37.95
23/03/2016	20	**4.00**	36.69
23/03/2016	21	**0.10**	36.69
24/03/2016	20	**0.10**	34.69
24/03/2016	21	**0.00**	33.69

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Table D.2 – *Continued from previous page*

25/03/2016	20	**0.00**	32.44
25/03/2016	21	**0.00**	32.44
29/03/2016	20	**0.10**	35.79
29/03/2016	21	**8.00**	44.69
30/03/2016	20	**0.00**	35.17
30/03/2016	21	**0.00**	35.35
31/03/2016	21	**0.00**	31.44
01/04/2016	20	**4.00**	35.18
01/04/2016	21	**4.50**	40.09
04/04/2016	20	**0.00**	29.69
04/04/2016	21	**0.00**	30.44
05/04/2016	21	**0.00**	29.69
06/04/2016	21	**0.00**	29.95
08/04/2016	21	**0.00**	23.89
09/04/2016	21	**0.00**	20.69
11/04/2016	21	**0.00**	24.03
12/04/2016	21	**0.00**	23.69
13/04/2016	20	**0.00**	21.89
13/04/2016	21	**0.10**	27.89
14/04/2016	20	**0.10**	28.09
14/04/2016	21	**4.00**	29.69
16/04/2016	21	**0.00**	23.69
17/04/2016	21	**0.00**	25.88
18/04/2016	21	**0.00**	23.69
19/04/2016	20	**0.00**	24.49
19/04/2016	21	**0.00**	26.12
20/04/2016	20	**0.00**	27.39
20/04/2016	21	**0.00**	28.69
21/04/2016	20	**4.50**	32.19
21/04/2016	21	**6.01**	41.69
22/04/2016	20	**0.00**	31.60
22/04/2016	21	**0.00**	35.69
25/04/2016	20	**0.00**	31.19
25/04/2016	21	**0.00**	31.19
26/04/2016	20	**0.00**	30.69

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Table D.2 – *Continued from previous page*

26/04/2016	21	**0.00**	31.45
27/04/2016	20	**4.50**	34.29
27/04/2016	21	**4.50**	35.29
28/04/2016	20	**0.00**	34.69
28/04/2016	21	**0.00**	34.69
29/04/2016	20	**0.00**	34.69
29/04/2016	21	**0.00**	34.69
02/05/2016	20	**4.00**	28.69
02/05/2016	21	**4.00**	30.69
02/05/2016	22	**0.00**	32.69
03/05/2016	20	**4.00**	31.69
03/05/2016	21	**4.00**	31.69
04/05/2016	20	**4.50**	33.19
04/05/2016	21	**6.63**	36.15
04/05/2016	22	**0.00**	41.50
05/05/2016	20	**4.50**	36.10
05/05/2016	21	**4.50**	36.29
06/05/2016	20	**0.00**	34.69
06/05/2016	21	**0.00**	34.87
09/05/2016	20	**0.10**	28.69
09/05/2016	21	**4.00**	30.89
10/05/2016	20	**4.50**	31.69
10/05/2016	21	**4.50**	32.19
11/05/2016	20	**4.00**	28.69
11/05/2016	21	**4.50**	34.69
12/05/2016	20	**0.00**	23.69
12/05/2016	21	**0.00**	26.69
16/05/2016	20	**0.00**	26.94
16/05/2016	21	**0.10**	27.94
17/05/2016	20	**0.00**	34.69
17/05/2016	21	**0.00**	34.69
18/05/2016	20	**0.00**	29.69
18/05/2016	21	**0.00**	30.69
19/05/2016	20	**0.00**	33.69
19/05/2016	21	**0.00**	34.80

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Table D.2 – *Continued from previous page*

20/05/2016	20	**0.00**	33.87
20/05/2016	21	**0.00**	33.87
23/05/2016	20	**4.00**	32.69
23/05/2016	21	**4.50**	33.69
24/05/2016	20	**0.00**	30.49
24/05/2016	21	**0.00**	30.79
25/05/2016	20	**0.00**	36.23
25/05/2016	21	**0.10**	36.69
26/05/2016	20	**0.00**	35.19
26/05/2016	21	**0.00**	36.19
27/05/2016	20	**0.00**	32.69
27/05/2016	21	**0.00**	32.00
30/05/2016	20	**0.10**	35.39
30/05/2016	21	**0.10**	34.69
31/05/2016	20	**0.00**	37.19
31/05/2016	21	**0.10**	38.29
01/06/2016	21	**0.00**	38.89
02/06/2016	20	**0.00**	40.69
02/06/2016	21	**0.00**	39.23
05/06/2016	21	**0.00**	41.00
15/06/2016	21	**0.00**	33.25
20/06/2016	21	**0.00**	42.96
23/06/2016	20	**0.00**	41.29
23/06/2016	21	**0.00**	38.95
30/08/2016	20	**0.00**	47.69
05/09/2016	20	**0.00**	47.83
05/09/2016	21	**0.10**	47.83
06/09/2016	21	**0.00**	51.19
12/09/2016	20	**0.00**	47.89
12/09/2016	21	**4.00**	50.60
14/09/2016	21	**0.00**	48.69
19/09/2016	20	**0.00**	46.19
19/09/2016	21	**0.00**	47.19
20/09/2016	20	**0.00**	47.69
20/09/2016	21	**0.00**	48.69

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Table D.2 – *Continued from previous page*

21/09/2016	20	**0.00**	48.69
21/09/2016	21	**0.00**	48.69
22/09/2016	20	**0.00**	48.69
22/09/2016	21	**0.00**	49.09
23/09/2016	21	**0.00**	49.19
26/09/2016	20	**0.10**	49.69
26/09/2016	21	**0.10**	49.87
27/09/2016	20	**0.00**	48.94
27/09/2016	21	**0.00**	48.69
28/09/2016	20	**0.00**	48.94
28/09/2016	21	**8.00**	50.69
29/09/2016	20	**4.50**	50.19
29/09/2016	21	**4.50**	51.69
01/10/2016	21	**0.00**	49.89
02/10/2016	21	**10.00**	52.69
03/10/2016	20	**10.00**	53.69
03/10/2016	21	**10.00**	55.99
04/10/2016	20	**8.00**	54.69
04/10/2016	21	**10.00**	55.99
05/10/2016	20	**8.00**	55.69
05/10/2016	21	**8.00**	56.09
06/10/2016	21	**4.00**	57.54
07/10/2016	21	**0.10**	58.89
10/10/2016	20	**10.00**	60.44
10/10/2016	21	**10.00**	64.79
11/10/2016	20	**0.00**	58.69
11/10/2016	21	**10.00**	62.69
12/10/2016	21	**10.00**	61.69
13/10/2016	20	**0.00**	60.90
13/10/2016	21	**8.00**	63.74
14/10/2016	21	**4.50**	63.21
16/10/2016	20	**0.10**	60.20
16/10/2016	21	**8.00**	62.69
17/10/2016	20	**10.00**	66.07
17/10/2016	21	**12.00**	69.69

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Table D.2 – *Continued from previous page*

18/10/2016	20	**0.10**	61.50
18/10/2016	21	**10.00**	64.69
19/10/2016	20	**0.00**	64.19
19/10/2016	21	**4.00**	66.10
20/10/2016	21	**4.50**	66.07
21/10/2016	21	**0.10**	66.19
22/10/2016	21	**0.00**	58.79
23/10/2016	21	**0.00**	63.19
24/10/2016	20	**0.00**	58.79
24/10/2016	21	**0.00**	60.69
25/10/2016	20	**10.00**	65.69
25/10/2016	21	**10.00**	68.09
26/10/2016	20	**0.10**	64.38
26/10/2016	21	**4.00**	65.89
27/10/2016	20	**4.00**	63.19
27/10/2016	21	**8.00**	65.20
28/10/2016	20	**4.00**	64.20
28/10/2016	21	**4.50**	65.89
29/10/2016	20	**10.00**	64.20
29/10/2016	21	**4.50**	64.89
31/10/2016	20	**4.50**	63.74
31/10/2016	21	**0.00**	61.69
01/11/2016	20	**8.00**	66.74
01/11/2016	21	**0.10**	65.89
02/11/2016	20	**8.00**	71.89
02/11/2016	21	**4.50**	71.89
03/11/2016	20	**0.10**	72.19
03/11/2016	21	**0.10**	72.19
04/11/2016	20	**0.00**	67.69
04/11/2016	21	**0.00**	67.69
06/11/2016	20	**0.00**	67.69
06/11/2016	21	**0.00**	65.69
07/11/2016	20	**0.00**	66.10
07/11/2016	21	**0.00**	66.10
08/11/2016	20	**0.00**	62.38

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Table D.2 – *Continued from previous page*

08/11/2016	21	**0.00**	62.38
09/11/2016	20	**0.00**	63.69
09/11/2016	21	**0.00**	64.69
10/11/2016	20	**0.10**	68.69
10/11/2016	21	**0.10**	69.19
11/11/2016	20	**0.00**	68.90
11/11/2016	21	**0.00**	68.64
12/11/2016	20	**0.00**	68.94
12/11/2016	21	**0.00**	66.71
14/11/2016	20	**0.00**	66.10
15/11/2016	20	**0.00**	67.79
15/11/2016	21	**0.00**	68.69
17/11/2016	20	**0.00**	69.32
21/11/2016	20	**0.00**	66.10
21/11/2016	21	**0.00**	66.10
28/11/2016	20	**4.00**	73.10
05/12/2016	20	**0.00**	71.22
05/12/2016	21	**0.00**	70.10
06/12/2016	20	**0.00**	72.69
06/12/2016	21	**0.00**	70.21
07/12/2016	20	**0.00**	69.99
10/12/2016	20	**0.00**	68.22
10/12/2016	21	**0.00**	68.22
12/12/2016	20	**0.00**	73.69
12/12/2016	21	**0.00**	73.69
13/12/2016	20	**0.00**	70.89
19/12/2016	20	**0.00**	71.69
19/12/2016	21	**0.00**	71.69
20/12/2016	20	**0.00**	71.20
21/12/2016	20	**0.10**	74.69
21/12/2016	21	**0.00**	72.69
22/12/2016	20	**0.00**	74.69
27/12/2016	20	**0.00**	72.10

D.2 Results for 2017

Table D.3: Infeasible results for scenario 3 in 2016.

Day	Hour	New Price (€/MWh)	Old Price (€/MWh)
03/01/2017	20	**0.00**	74.29
03/01/2017	21	**0.00**	74.76
04/01/2017	20	**0.00**	73.69
05/01/2017	20	**0.10**	76.10
05/01/2017	21	**0.00**	73.69
07/01/2017	20	**0.00**	77.69
08/01/2017	20	**0.00**	74.69
09/01/2017	20	**0.10**	80.10
09/01/2017	21	**0.00**	76.10
11/01/2017	20	**4.00**	88.44
11/01/2017	21	**0.10**	83.19
16/01/2017	20	**0.00**	83.69
16/01/2017	21	**0.00**	83.69
17/01/2017	21	**0.00**	85.19
20/01/2017	20	**0.00**	98.69
20/01/2017	21	**0.00**	98.19
23/01/2017	20	**0.00**	96.19
23/01/2017	21	**0.00**	97.19
24/01/2017	20	**0.00**	98.19
24/01/2017	21	**0.10**	99.10
26/01/2017	20	**0.10**	93.89
26/01/2017	21	**4.00**	95.05
28/01/2017	20	**0.00**	79.94
28/01/2017	21	**0.00**	79.35
29/01/2017	20	**0.00**	79.35
29/01/2017	21	**0.00**	79.94
30/01/2017	20	**0.10**	86.70
30/01/2017	21	**0.10**	84.95
31/01/2017	20	**10.00**	89.10
31/01/2017	21	**4.00**	83.69
01/02/2017	20	**4.00**	77.10

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Table D.3 – *Continued from previous page*

01/02/2017	21	**0.00**	75.10
02/02/2017	20	**0.00**	60.79
02/02/2017	21	**0.00**	61.19
03/02/2017	20	**0.10**	58.29
05/02/2017	20	**0.10**	59.69
05/02/2017	21	**0.00**	57.28
06/02/2017	20	**8.00**	62.19
06/02/2017	21	**8.01**	63.74
07/02/2017	20	**0.00**	63.19
07/02/2017	21	**0.00**	64.19
08/02/2017	20	**8.00**	70.54
08/02/2017	21	**8.00**	72.60
09/02/2017	21	**0.00**	67.23
10/02/2017	20	**4.00**	69.94
10/02/2017	21	**0.10**	69.69
11/02/2017	20	**0.00**	59.12
11/02/2017	21	**0.10**	60.19
13/02/2017	20	**8.00**	67.90
13/02/2017	21	**8.00**	67.90
14/02/2017	20	**0.00**	63.37
14/02/2017	21	**0.00**	65.11
15/02/2017	20	**0.10**	64.69
15/02/2017	21	**0.10**	65.11
16/02/2017	20	**8.00**	69.40
16/02/2017	21	**4.50**	66.10
17/02/2017	20	**8.00**	66.21
17/02/2017	21	**8.00**	66.21
19/02/2017	20	**0.00**	60.69
19/02/2017	21	**4.50**	62.19
20/02/2017	20	**0.10**	59.94
20/02/2017	21	**0.00**	59.94
21/02/2017	20	**8.00**	60.61
21/02/2017	21	**4.50**	60.61
22/02/2017	20	**10.00**	61.86
22/02/2017	21	**10.00**	61.69

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Table D.3 – *Continued from previous page*

23/02/2017	20	**0.00**	59.19
23/02/2017	21	**0.00**	59.36
24/02/2017	20	**4.00**	58.19
25/02/2017	20	**0.00**	57.69
25/02/2017	21	**0.00**	58.11
28/02/2017	20	**0.00**	52.69
28/02/2017	21	**0.00**	52.69
02/03/2017	20	**0.00**	57.56
06/03/2017	20	**0.10**	54.35
06/03/2017	21	**0.00**	54.35
07/03/2017	20	**0.00**	53.74
07/03/2017	21	**0.10**	55.71
08/03/2017	20	**4.00**	55.44
08/03/2017	21	**4.00**	55.49
10/03/2017	20	**0.00**	53.56
10/03/2017	21	**0.00**	54.69
13/03/2017	20	**0.00**	46.89
13/03/2017	21	**0.00**	48.56
14/03/2017	21	**0.00**	50.96
15/03/2017	20	**0.00**	51.96
15/03/2017	21	**0.00**	52.46
16/03/2017	21	**0.00**	51.25
23/03/2017	20	**0.00**	51.96
23/03/2017	21	**0.10**	53.69
27/03/2017	21	**0.00**	55.19
10/04/2017	21	**0.00**	51.87
07/09/2017	21	**0.00**	52.50
11/09/2017	21	**0.00**	51.20
12/09/2017	21	**0.00**	53.60
16/09/2017	21	**0.00**	51.89
18/09/2017	20	**0.10**	52.51
18/09/2017	21	**0.10**	54.01
19/09/2017	21	**0.10**	55.12
26/09/2017	21	**0.00**	58.42
27/09/2017	21	**0.00**	59.11

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Table D.3 – *Continued from previous page*

02/10/2017	20	**0.10**	60.79
02/10/2017	21	**10.00**	64.00
10/10/2017	21	**0.00**	70.00
16/10/2017	21	**0.00**	68.54
17/10/2017	21	**0.00**	68.54
18/10/2017	20	**0.00**	68.54
23/10/2017	20	**0.00**	71.39
20/11/2017	20	**0.00**	78.79
24/12/2017	21	**0.00**	70.19

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