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ELECTRICITY WHOLESALE IMPACTS OF AGGREGATION OF ELECTRIC VEHICLES

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ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
MASTER IN THE ELECTRIC POWER INDUSTRY

Master's thesis

ELECTRICITY WHOLESALE IMPACTS OF AGGREGATION OF ELECTRIC VEHICLES

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Contents

List of tables ii
List of figures iii
Resumen i
Abstract iii
I. Introduction and motivation 1
II. State of the art 3
  A. What is an aggregator? 3
  B. What is the actual state of Electric Vehicles? 5
    1. Projections of future EV penetration Globally and in Spain. 8
  C. What are the main components of a retail tariff? 10
  D. How are batteries modelled? 13
III. ROM Model 15
IV. Definition of case studies 19
  A. Tariff designs 19
    1. Spanish tariff 19
    2. Modelling of the Spanish tariff 20
    3. Efficient network tariff. 21
  B. Methodology 22
  C. Input data 22
    1. Demand 22
    2. Electric Vehicles 23
    3. Renewable generation 24
V. Results 25
  A. No tariff, Locational Marginal Prices. Reference case. 25
    1. Thermal generation costs 25
    2. Losses in the system 25
    3. Marginal prices 25
    4. Electric Vehicle behavior 27
    5. Emissions 29
    6. Non-served energy 29
  B. Spanish tariff, single node price. 29
    1. Thermal generation costs 30
    2. Losses in the system 30

3. Marginal prices ... 31
4. Electric Vehicle behavior ... 32
5. Emissions ... 34
6. Non-served energy ... 34
C. Efficient tariff, single node price ... 34
1. Thermal generation costs ... 34
2. Losses in the system ... 35
3. Marginal prices ... 35
4. Electric Vehicle behavior ... 36
5. Emissions ... 37
6. Non-served energy ... 37
D. Efficient tariff, Locational Marginal Prices ... 37
1. Thermal generation costs ... 38
2. Losses in the system ... 38
3. Marginal prices ... 38
4. Electric Vehicle behavior ... 40
5. Emissions ... 41
6. Non-served energy ... 42
E. Reference case with no tariff and no degradation modelling, LMP pricing. ... 42
1. Thermal generation costs ... 42
2. Losses in the system ... 42
3. Marginal prices ... 42
4. Electric Vehicle behavior ... 43
5. Emissions ... 45
6. Non-served energy ... 45
F. Summary ... 45
VI. Conclusions ... 47
A. How does battery degradation affect EV behavior? ... 47
B. How do tariffs affect the behavior of EVs and what benefits can be extracted for the system? ... 47
VII. Future work ... 49
References ... i
Annex I ... ii

List of tables

Table 1: BEV characteristics used in this thesis. 15
Table 2: Future projections made for the Spanish GDP by the Ministry of Economy, Industry and Competitiveness and the OECD. Table from (IIT, 2017). 23
Table 3: Demand and EV generation and consumption for no tariff simulation. 25
Table 4: Average marginal prices per node. 25
Table 5: Average hourly marginal prices. No tariff simulation. 27
Table 6: BEV hourly average consumption and generation vs hourly average marginal prices. No Tariff simulation. 28
Table 7: Demand and EV behavior for the study with the Spanish tariff and single node pricing. 30
Table 8: Losses for the Spanish tariff with single pricing scheme. 30
Table 9: Average hourly marginal prices for the Spanish tariff with single pricing scheme simulation. 31
Table 10: EV behavior compared with the average marginal prices for each hour. Spanish tariff with single node price. 32
Table 11: Demand and BEV behavior for the efficient tariff with single node pricing. 34
Table 12: Average hourly marginal prices. Efficient tariff with single node pricing. 36
Table 13: Average EV consumption and generation for every hour of the day. Efficient tariff with single node pricing. 37
Table 14: System demand and EVs generation and consumption. Efficient tariff with LMP. 38
Table 15: Average yearly marginal prices for each node of the system. Efficient tariff with LMP. 39
Table 16: Average yearly marginal prices for each hour of the day in the aggregators node. Efficient tariff with LMP. 40
Table 17: EV behavior and pattern. Efficient tariff with LMP. 41
Table 18: System demand and EV generation and consumption for the simulation with no degradation effect. 42
Table 19: Comparison between marginal prices from the reference case with degradation and no degradation modelled. 43
Table 20: Comparison between reference case studies with degradation and without. 44
Table 21: Main features for comparison between the different simulations. 45
Table 22: EV behavior comparison between all the simulations. 46
Table 23: Percent of range used of EVs every hour. ii
Table 24: Percent of EVs plugged to the grid at every hour. ii

List of figures

Figure 1: Briefing of the three types of value creation possibilities in aggregators. Figure taken from (Burger, et al., Jan 2016). 5
Figure 2: Evolution of the global electric car stock from 2010 to 2015. Graph from (International Energy Agency, 2016). 6
Figure 3: Investments in shared mobility. Graph from (McKinsey&Company, October 2016) 7
Figure 4: Evolution of battery energy density and cost. Graph from (International Energy Agency, 2016) 8
Figure 5: EV penetration projections for some companies and public institutions. Data from (BP, 2017) and (International Energy Outlook 2016, 2017) 9
Figure 6: Components of the electricity production price for the year 2016. Data from Esios, REE. 11
Figure 7: Average electricity bill for a household consumer. 2.0 A access tariff, 3,3 kW contracted capacity. 12
Figure 8: ROM inputs and outputs. Source: (Castro Cerdas, 2016). 17
Figure 9: Simplified grid representation of the ROM. Figure from (Castro Cerdas, 2016). 18
Figure 10: EV tariff vs the wholesale spot price in Spain. Red is the spot price in Spain for 1/June/2017 and grey is the EV tariff applied to consumers. Graph from Esios (REE). 20

Resumen

El sector energético está sufriendo importantes cambios, estos cambios no sólo están afectando a la forma en la que generamos la energía, cambiando de los combustibles fósiles a energías renovables y sostenibles medioambientalmente, sino que van más allá; son cambios en como consumimos la energía que necesitamos, en el comportamiento energético de los consumidores. Se pretende que en esta nueva transición energética el consumidor se convierta en un agente activo más y una gran forma de hacerlo es a través de los recursos distribuidos que pueden instalar. Uno de estos recursos distribuidos son los coches eléctricos con una batería capaz de almacenar energía, lo que da lugar a posibilidades que antes los consumidores no tenían.

Por este motivo, y debido a la preocupación que suscita la futura penetración y evolución de los vehículos eléctricos se están realizando varios estudios acerca de que beneficios se pueden extraer de la operación eficiente de la carga y descarga de las baterías de los vehículos eléctricos y que efectos pueden tener sobre las redes de distribución. Las baterías de estos vehículos podrían proporcionar beneficios varios a la red y los usuarios, entre ellos, la reducción de la volatilidad de precios gracias a la capacidad de almacenar energía barata para cubrir necesidades en periodos de precios más altos.

Sin embargo, la señal de precio que reciben los consumidores residenciales, y, por tanto, los dueños de los vehículos, tiene más componentes que el simple coste de producción de la electricidad. En la tarifa española se añade un término volumétrico para la recuperación de partes del coste de la red, tanto de distribución como de transporte. Se ha encontrado que esta tarifa distorsiona la señal de precios que reciben los consumidores, no promoviendo su flexibilidad y evitando que se pueda beneficiar el sistema de la capacidad de almacenamiento de los vehículos eléctricos.

Sí que es cierto que la tarifa implementada actualmente en el sistema español incentiva, y así se ha comprobado, la carga durante las horas nocturnas y penalizando la carga durante el día evitando que los precios suban. Esta tarifa también intenta incentivar que se pueda almacenar parte de la energía consumida por la noche para reducir los precios en las horas punta del día, pero

la diferencia de precios que finalmente ve el consumidor no promueve tal comportamiento salvo en horas con precios muy elevados.

En la tesis se realiza el análisis con otra tarifa presentada en (Castro Cerdas, 2016) la cual se llegó a la conclusión de que era más eficiente y menos distorsiva mientras que a la vez permitía recuperar los costes de la red.

Con esta tarifa se ha encontrado que ciertamente hay una ligera distorsión, ya que se penaliza con un término de capacidad las horas en las que el consumo horario que asume un coste marginal de largo plazo y se asigna en horas puntas del sistema cuando las redes tienen menos margen disponible, pero al no haber un término volumétrico que aplique a todas las horas la distorsión es menor y la señal de precios que ven los consumidores es más eficiente, lo cual incentiva que se consuma en las horas de menor coste y se produzca en las de mayor coste para así reducir la volatilidad de los precios y siendo posible reducir la factura eléctrica.

También se ha realizado un análisis teniendo en cuenta dos posibilidades con dos estructuras de fijación de precios diferentes: nudo único, en la que los precios marginales de todos los nudos son iguales y de precios nodales, donde cada nudo tiene su propio precio marginal.

Tras este análisis se ha comprobado que el nudo único distorsiona el comportamiento de los vehículos eléctricos a la hora de generar y consumir energía. Con este sistema de fijación de precios, el vehículo eléctrico ya no puede aprovechar la diferencia de precios que se acrecienta por el efecto de las pérdidas modeladas de manera cuadráticas al flujo entre nudos para obtener beneficio, sino que solo se fija en al margen de precios que haya dentro de su propio nudo.

Aun así, la distorsión que crea el sistema de nudo único es mucho menor que el creado por la tarifa española, por ello se propone un paso intermedio entre la solución más eficiente (precios nodales y tarifa eficiente) y la actual (tarifa española con sistema de precio único). Este paso intermedio se basa en un sistema de precio único, pero con la tarifa eficiente.

Abstract

The energy sector is changing importantly, but these changes do not occur uniquely in the generation of the energy we use by changing from fossil fuels to more sustainable and cleaner energy sources. The changes are also occurring at demand level, in the way consumers use the energy they demand and the behavior of the demand. With the new energy transition that is taking place the idea is that consumers become active agents and a way to start doing this is through the distributed energy sources that they have access to and can install. One of these distributed sources are electric vehicles, with a battery capable of storing energy and delivering new possibilities for the behavior of consumers.

For this reason and due to the increasing worry that the future penetration of electric vehicles in the distribution grid, many studies are being made to assess the impact of the vehicles in the system and which benefits we can extract from the correct and efficient operation of electric vehicles. Batteries from the vehicles are an important asset for the system since they allow to store cheap energy to later on give it back to the system in hours of higher prices. In the current situation, EVs don't have the possibility of injecting energy back to the grid, manufacturers still don't offer this possibility and the necessary procedures from utilities and aggregators have not still been adapted

The price signal experienced by final consumers has more components than the production cost of the energy, these components aim to recover the network costs and other regulated costs. In the Spanish case a volumetric charge is included in the access tariff to recover part of the network and other regulated costs. This component has been found to be distortive for the behavior of EVs, not promoting its flexibility.

The Spanish access tariff specifically implemented for EV charging accomplishes its objective in the way that consumption from EVs is mainly incentivized at night hours when the wholesale price and the volumetric charge are lower, penalizing EV charging at high price hours by increasing the tariff volumetric component at those hours. Despite that, in this thesis has been analyzed that the spread in prices observed in the Spanish market until now would not be enough to compensate for battery losses and the degradation effect that batteries would experience.

In addition to the previously described study, in this thesis another analysis has been made with the tariff design presented in (Castro Cerdas, 2016). This design is more efficient and less distortive than the current design and at the same time allows to recover the network costs. The efficient design recovers 20% of the network costs with a peak demand charge to the consumers and the other 80% and the other regulated costs as a fixed charge with no volumetric component.

In this second case, there is still some distortion with the efficient tariff due to the penalization included at the hours with higher EV demand, but by not being a volumetric term at every hour the distortion is lower and the energy price signal is less distorted., This incentivizes to consume more energy, i.e. charge the batteries, at the lowest price hours to later on deliver it back to the grid when prices reach a sufficiently high level, reducing price volatility.

Finally, in the thesis has been carried out an additional study, comparing two different energy pricing schemes: single node pricing and locational marginal prices (nodal pricing).

From this study, it has been concluded that the single node pricing distorts the behavior of the agents when generating and consuming energy more than nodal pricing. With single node pricing, electric vehicles cannot take advantage of price differences that would be experienced with nodal prices. In particular, price differences s between the transmission system where most generation is connected and the aggregator node located at distribution where EVs are connected.

As final conclusion, the distortion created by adopting a single node pricing is much lower than the one created by the current Spanish tariff, therefore this thesis recommends an intermediate solution to be implemented. This intermediate solution between the most efficient design (efficient network tariff and nodal energy prices) and the current system (Spanish access tariff and single energy price) would be based on a system where the efficient network tariff is implemented but the pricing scheme in Spain would continue to be single node pricing,

I. Introduction and motivation

Industries have experimented changes along history, some of them getting to the point of disappearing and leaving space to new industries or transforming radically into a new type of industry. Changes, therefore, are present in every type of industry and the electricity sector is not absent of them. Undoubtedly, the electric industry has been experiencing changes for some years, changes which are expected to go deeper and extend their influence.

Some of these transformations are: the so called “smart grids”, more renewable energy models, the introduction of distributed generation connected to current grid or the increasingly demand elasticity with different means of “demand side management” tools are now possible thanks to new technological advances and the liberalization of the retail and wholesale markets.

The present and future evolution of the system is an important subject of study nowadays, studies not only done by universities for academic purposes but also by government agencies, institutions and multinational companies from all over the world. Some of the relevant topics are the capacity of actual networks to take care of generation connected to distribution networks (i.e. distributed generation) and how its connection affects the rest of the system or the capability of the system to introduce electric vehicles and batteries.

This study is meant to give some light in the aspects mentioned above for the Spanish system. The aim of this study is to measure the operational impacts of the aggregation of distributed energy sources on the power system making simulations and analyzing the results of a model provided by the IIT from the Universidad Pontificia Comillas in Madrid, the ROM (Reliability Operation Model). There will be two different modellings within the ROM, the first one considers a simplified distribution grid representation to account for energy losses and nodal pricing, the second one will be more like the model used for the Spanish system, a single node price.

The source studied in depth will be the electric vehicle since it is a recent concern for today´s power systems because it is considered a good ally against air pollution in the cities and their batteries can be used as storage units. The complexity of this is that not every single car owner uses its car in the same hours and when it uses it, doesn't travel the same distance. Electric vehicles(EVs), have different tariffs than the rest of the loads in Spain so its behavior is conditioned by this tariff and how the tariffs are designed.

This thesis is the continuation of one a student from this same University made a year ago; Juan José Castro Cerdas, in this the thesis which is titled: "Retail Prices Design in a Context of Flexible Consumers, Impacts on the Bulk Power System: a Spanish Case Application" from now on (Castro Cerdas, 2016), he studied how different tariff designs affect the behavior and interaction with the system of some flexible consumers, aggregated in a single node that manages their flexible resources. At the same time, it analyzed how these different tariff designs affect the system losses and costs.

This thesis focuses on EVs and how different charging strategies, alongside with the different tariffs proposed in (Castro Cerdas, 2016) impact the system and the behavior of EVs.

II. State of the art

The study in which this thesis has its main basis is “*Retail Prices Design in a Context of Flexible Consumers, Impacts on the Bulk Power System: a Spanish Case Application*” from Juan José Castro Cerdas. As it has been mentioned before, that thesis mainly focuses on how to design different tariffs and how these designs affect the system operation and costs. In that study, Castro Cerdas didn´t focus on a single type of distributed energy resource, consequently, in the aggregator node there is not only demand but also some solar PV generation and electric vehicles which can enable the demand to have some more flexibility in its consumption from the network. In this way, not only demand can benefit by reducing its consumption from the network but also the system is benefited since losses can get reduced and therefore, system costs.

A. What is an aggregator?

Mainly, an aggregator is an agent that manages the different distributed energy sources of different customers or other agents that pay for it.

According to (European Commission, Feb 2017) an aggregator is a *“market participant that combines multiple customer loads or generated electricity for sale, for purchase or auction in any organised energy market.”*

There are other definitions that can be given to aggregators, for example, in (Burger, et al., Jan 2016) in which the definition is taken from (Ikäheimo, et al., 2010): *“an aggregator is a company who acts as an intermediary between electricity end-users and DER owners and the power system participants who wish to serve these end-users or exploit the services provided by these DERs”*.

Thanks to the concentration of distributed resources the aggregator can benefit from economies of scale and is able of having an impact in the system operation thanks to its own operation and management of the distributed energy sources. In this way, aggregators are also able of reducing its customers’ final electricity bill. There are different ways in which the aggregator can achieve such a thing. A simple example, producing with EVs when the price is high and recharging them when the price is low.

Since batteries from Electric Vehicles (EVs) have a degradation related to each kWh used and that energy is not infinite, aggregators have to be able to optimize and take care of the use they are making of EV's batteries or solar energy is the most efficient.

However, this is a simplistic example. Burger, et al. (Jan 2016) considered that aggregators can introduce three different types of value creation to the system and its agents, the first one is called "fundamental" value; also called "intrinsic" value because it does "not depend on the specific regulations, level of market awareness of consumers or technologies in place in the power system, and will be permanent or near permanent in time". This type of value can only be achieved in advanced system, where information flows are perfect, agents behave completely rationally and regulations, if existent, are perfect. The second type of value creation is called "transitory" value; which contributes to the well-functioning of the market under the present conditions. And the third type of value creation described in (Burger, et al., Jan 2016) is called the "opportunistic" value creation, and takes advantage of regulatory or market failures.

In Figure 1, a schematic summary of the concepts of these three types of value creation is given.

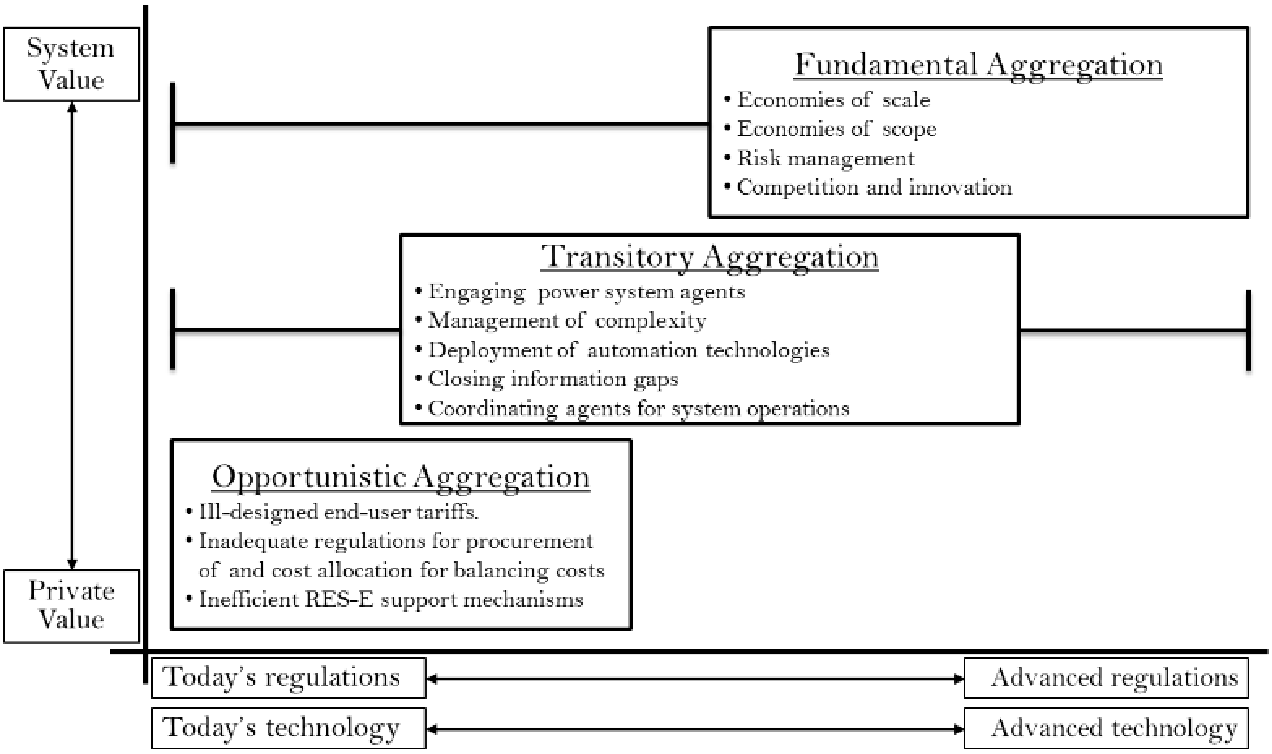
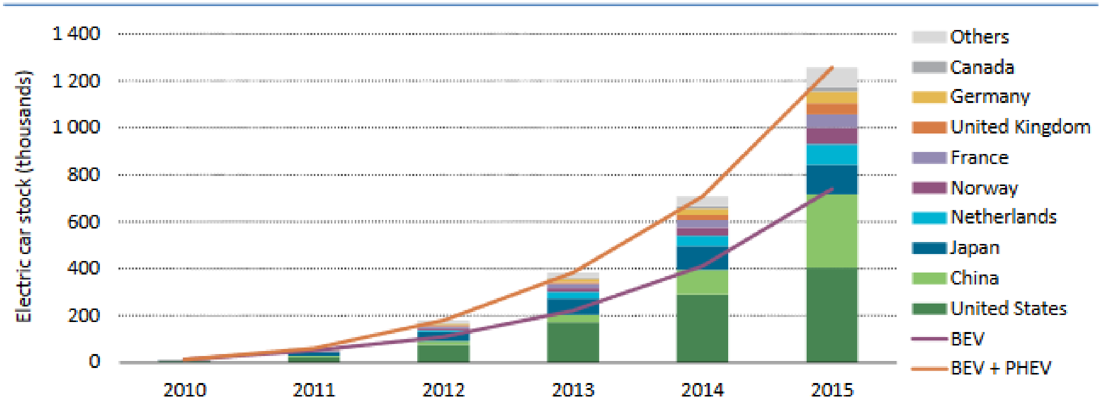


Figure 1: Briefing of the three types of value creation possibilities in aggregators. Figure taken from (Burger, et al., Jan 2016).

In the proposal from the European Commission, (European Commission, Feb 2017), Article 13 shows the minimum terms that contracts with aggregators should have to ensure a fair behavior with the consumers/clients and a good functioning of the market, meaning that customers should be able to arrange and conclude a contract with an aggregator without the suppliers permission, and in case of conclusion, termination should be entitled within 3 weeks and the client should not be charged a termination fee that exceeds the direct aggregator's loss.

B. What is the actual state of Electric Vehicles?

According to the International Energy Agency in its Electric Vehicle Outlook from 2016, the global EV stock grew to above 1 million cars, more precisely, over 1.2 million EVs. Around more than 50% of the global EV stock comes from Pure Battery Electric Vehicles, over 700 million cars. As it can be seen in Figure 2 the growth since 2010 has followed a nearly quadratic increment. Between 2015 and 2014 the registration of new electric cars grew by a 70%, which means 550 thousand new electric cars globally.



Note: the EV stock shown here is primarily estimated on the basis of cumulative sales since 2005.

Sources: IEA analysis based on EVI country submissions, complemented by EAFO (2016), IHS Polk (2014), MarkLines (2016), ACEA (2016a), EEA (2015) and IA-HEV (2015).

Figure 2: Evolution of the global electric car stock from 2010 to 2015. Graph from (International Energy Agency, 2016).

To keep up with this favorable evolution of EVs, policy support is still needed. According to (International Energy Agency, 2016) it is complicated to assure which is the best way to incentivize EV uptake, but two factors appear to be fundamental for the introduction of EVs in the markets: financial incentives and the availability of charging infrastructures.

McKinsey&Company (October 2016) and BP (2017) give some future perspective on how the future of mobility can transit. McKinsey&Company (October 2016) talks about 3 drivers that will shape the future of mobility: car-sharing and car-pooling, electrification and autonomous driving. These 3 drivers are also explored by BP in their mobility revolutions. Both seem to agree in the paradigm change that the strong irruption of these 3 drivers can thrive.

Within these new revolutions that BP and McKinsey explore the ownership is less valued, what is sought is the use of the asset at the lowest price possible, being able to go from one place to another in different transportation modes and respecting the environment. In this sense, McKinsey shows the explosion of this new market with graphs where the exponential increase in investments of these types can be seen (Figure 3).

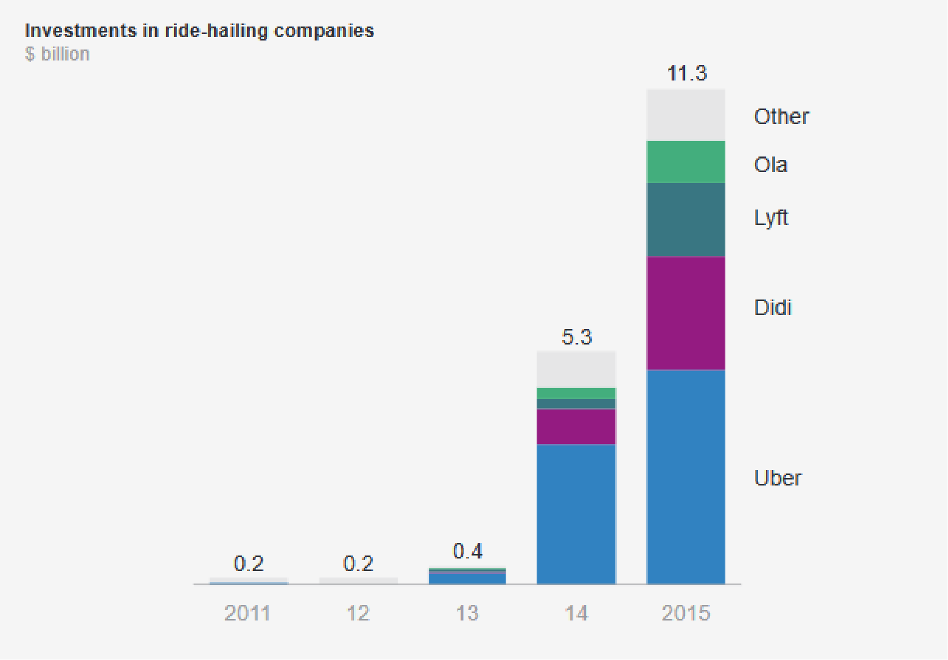
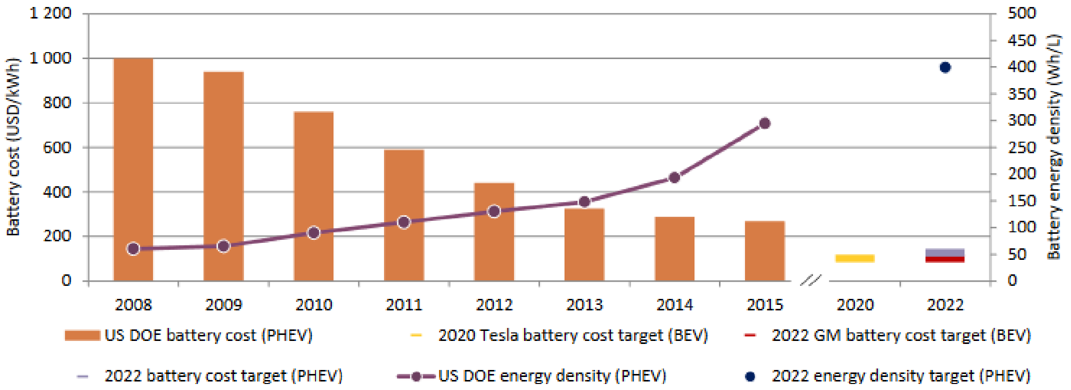


Figure 3: Investments in shared mobility. Graph from (McKinsey&Company, October 2016)

As EV costs decrease and get closer to the costs of Internal Combustion Engine cars (ICE), the financial incentives must be reduced progressively. The same happens with the rest of policy incentives for EVs so as they don't lose effectiveness and get to the point of having reverse impacts.

Battery costs for EVs are expected to decrease substantially as it can be seen in Figure 4. Alongside with the decrease in costs, it is also expected that battery density increases, what would help to diminish the aversion effect that the low autonomy of EVs causes. General Motor and Tesla have set targets related to the cost of batteries in 100 $/kWh, Tesla expects to reach it in 2020, and GM in 2022.



Notes: USD/kWh = United States dollars per kilowatt-hour; Wh/L = watt-hours per litre. PHEV battery cost and energy density data shown here are based on an observed industry-wide trend, include useful energy only, refer to battery packs and suppose an annual battery production of 100 000 units for each manufacturer.

Sources: US DOE (2015 and 2016) for PHEV battery cost and energy density estimates; EV Obsession (2015); and HybridCARS (2015).

Figure 4: Evolution of battery energy density and cost. Graph from (International Energy Agency, 2016).

1. Projections of future EV penetration Globally and in Spain.

From analyzing and reading what some other agencies and institutions have to say about the future of EVs, there is not much positivism about its future penetration. The International Energy Agency and BP in its Energy Outlook mention some projections for EV penetration. Both agencies in their reference scenarios do not think that the global penetration is going to go above the 8% of the mobile park, but this is a global reference, these agencies consider that the countries that should go ahead the penetration of EVs are the most developed ones, between them, European countries.

The next figure shows the projections of these two agencies in their reference scenarios and in more optimistic scenarios for EV penetration and decarbonization.

In Spain, the transport activity is the one that has the highest emissions, around a 24% of the total emissions in Spain, and it is the activity that has less reduced these emissions, only a 8% compared to over a 30% that the generation of electricity and the industry activities have achieved in the past 15 years.

According to (Monitor-Deloitte, March 2017), the transport sector needs and can achieve higher decarbonization objectives. This reduction of emissions in transport is vital for the correct completion of the objectives, says the study.

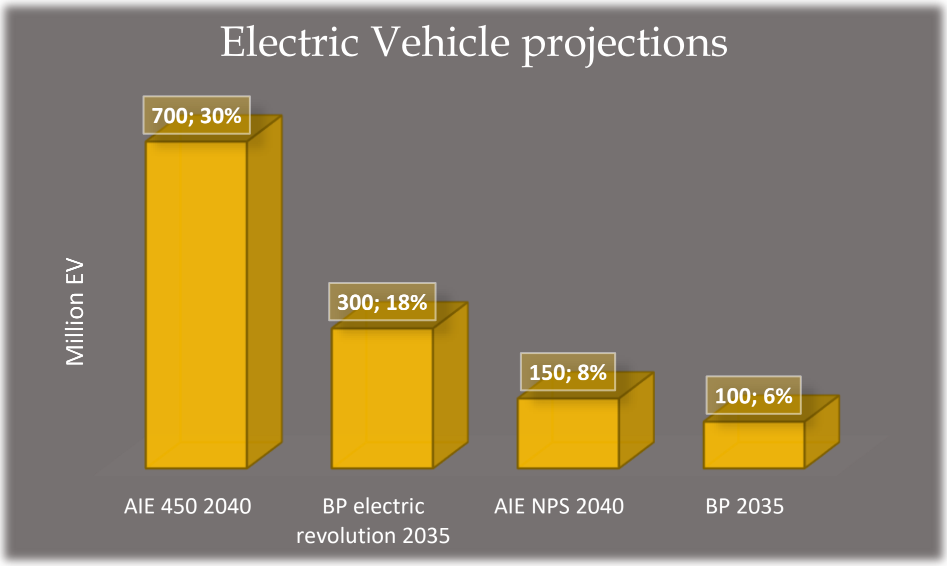


Figure 5: EV penetration projections for some companies and public institutions. Data from (BP, 2017) and (International Energy Outlook 2016, 2017)

Monitor-Deloitte (March 2017) considers that the transport sector is technically more mature and has lower renovation cycles than other activity sectors like industry or edification, these two factors provide the transport sector with a perfect starting point to start its decarbonization.

As it has been discussed before, Monitor-Deloitte (March 2017) also agrees that the electrification of the transport sector and the future developments of the digitalisation are going to mark the future evolution of EV penetration. This is an issue that also is presented in (BP, 2017), in which two different techonology revolutions are presented for the transport sector: the digital revolution and the electric revolution:

- Digital revolution: In this revolution the autonomous cars, ride sharing and car-pooling evolve at higher rates than expected, this would promote higher efficiency in the use of the vehicles and would at the same time reduce the cost for its utilization. The same idea behind this revolution is presented in (McKinsey&Company, October 2016) and exposed in (Monitor-Deloitte, March 2017), where the property is less valued and everything is connected.

- Electric revolution: In this revolution BP suggests that EV penetration increases substantially and that the technology presented in the digital revolution is only introduced with Electric Vehicles. This would cause two effects: the cost reduction of the use of EVs and a higher efficiency in its use.

Therefore, a change in paradigm is coming and the effects in the decarbonization and demand are still difficult to forecast, but these 3 agencies and companies named seem to agree in that the digitalization and the electrification of transport will change our way of transporting.

International Energy Agency (2016) and Monitor-Deloitte (March 2017) expose another development that is necessary for the development of the EV: the infrastructure for its charging.

Monitor-Deloitte calculated that for the correct evolution of EV in the spanish system a total of 90.000 public charging points are necessary.

C. What are the main components of a retail tariff?

The final electricity bill that customers receive is composed by 3 main components and not only by the unique cost of producing electricity. In order to calculate how much is going to be the final bill, consumers pay for different costs, such as the transmission and distribution grids which enable the consumer to receive the electricity, and different subsidies and costs that, depending on the country, can come from renewables, extra costs or some moratorium of certain generation sources, such as nuclear.

Following this logic and the structure presented by (Castro Cerdas, 2016) we can distinguish 3 types of charges that are paid in the final Spanish consumer bill.

- Energy prices: This accounts for the price of the electricity production and includes the day-ahead market clearing price, the intraday market price and ancillary services like the secondary reserve cost and the interruptability payments between others. In Figure 6 the main components of the Spanish production costs in €/MWh can be seen.

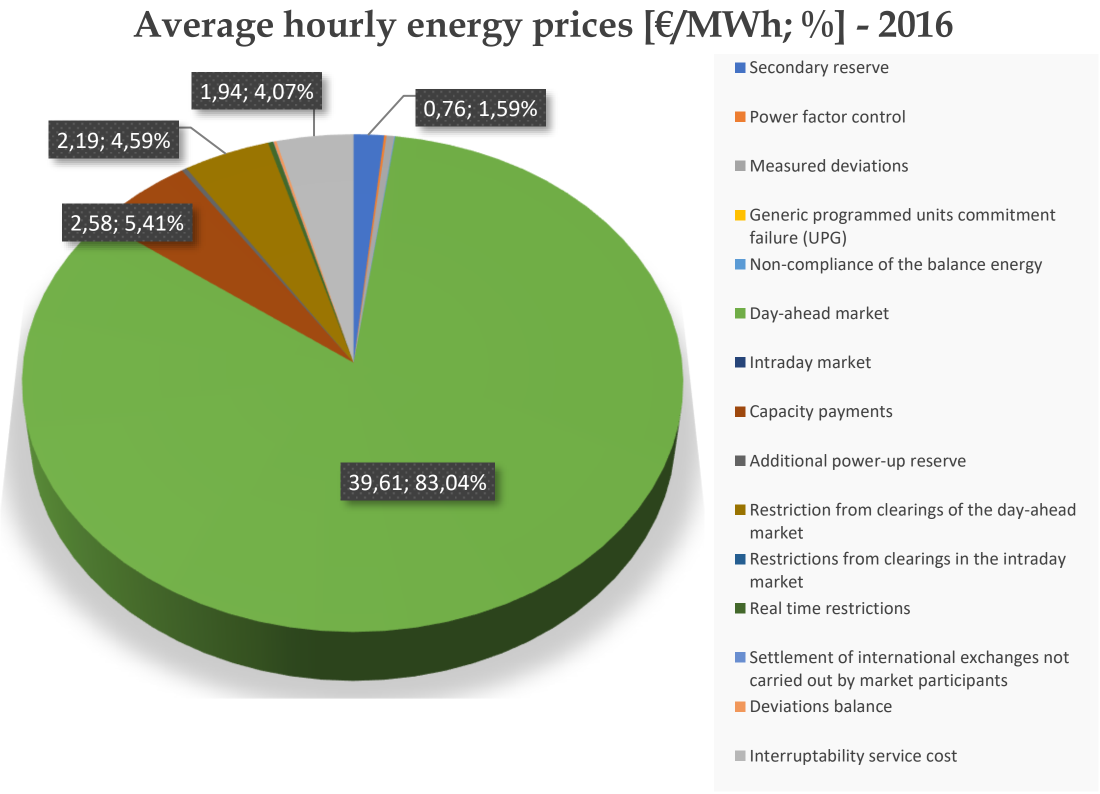


Figure 6: Components of the electricity production price for the year 2016. Data from Esios, REE.

- Network charges: It corresponds to the part of the tariff that the consumers pay and is used to pay for the costs of the transmission and distribution networks. In the Spanish tariff, there are two different concepts paid, decided by the Ministry:
    - A capacity charge given in €/kW.
    - An energy charge given in €/kWh.
- Other regulated charges: This other part includes the payment of taxes, remuneration for the Market Operator, the System Operator and the Regulator, subsidies for renewables and the accumulated tariff deficit in Spain. It is also decided by the Ministry.

For a household consumption, the network charges and the other regulated charges account for around a 50% of the final electricity bill.

In Figure 7 the consumption of an average electricity bill is shown with the PVPC, along with a decomposition of the different charges applied for a 56,97 € bill with a contracted capacity of 3,3 kW and the 2.0 A access tariff, the simple one for consumers with a contracted capacity lower than 10 kW and with no hourly discrimination. The energy consumption for this bill is 294 kWh.

By not behaving as a self-consumption consumer[1] the access tariff applied is the one marked in *IET/107/2014*. Self-consumption agents and non-self-consumption agents apply a different charge quantity under the current regulation.

The retailer margin applied is the one described in *Real Decreto 216/2014* and the PVPC calculation procedure is described in *Real Decreto 216/2014*.

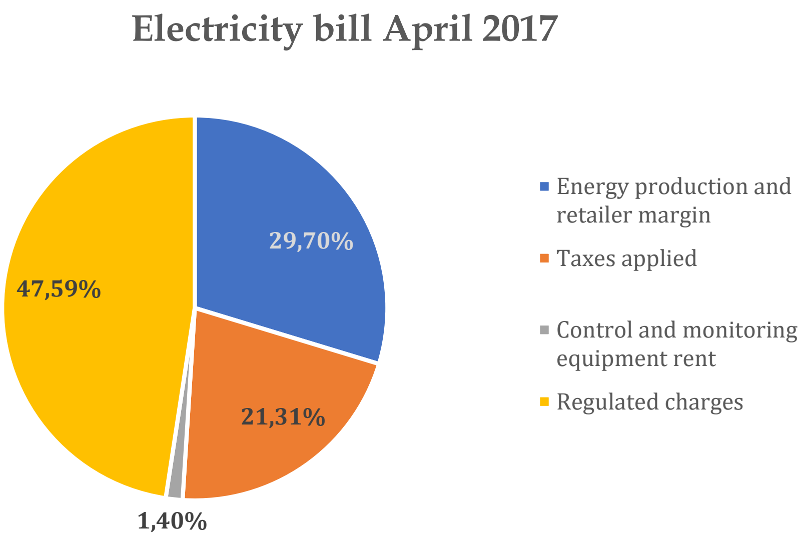


Figure 7: Average electricity bill for a household consumer. 2.0 A access tariff, 3,3 kW contracted capacity.[2]

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[1] According to article 9 of Law 24/2013 of the Electric Sector: a self-consumption consumer is a consumer that has a self-generation installation connected to the interior of its supply point and that doesn't have the credential as a production facility in the corresponding registration point. Therefore, only a unique agent is considered, called the consumption agent.

[2] Data taken from a real electricity bill for April 2017 from the city of Madrid.

D. How are batteries modelled?

Before entering into the mathematical modelling, a good understanding of battery specification concepts is useful. The paper used for many of the concepts is (MIT Electric Vehicle team, 2008).

- State of Charge (SOC) [%] → An expression of the present battery capacity as a percentage of maximum capacity.
- Depth of Discharge (DOD) [%] → The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge.
- C- and E- rates → In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour.
- Nominal Voltage [V] → The reported or reference voltage of the battery, also sometimes thought of as the "normal" voltage of the battery.
- Cut-off Voltage → The minimum allowable voltage. It is this voltage that generally defines the "empty" state of the battery.
- Terminal Voltage [V] → The voltage between the battery terminals with load applied. Terminal voltage varies with SOC and discharge/charge current.
- Capacity or Nominal Capacity (Ah for a specific C-rate) → The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage.

- End Of Life (EOL) → Due to degradation, batteries diminish their total maximum capacity each time they are used. Depending on the manufacturer it can be around 70%. In this case study we will use 80% as it is defined in (Beer, et al., 2012).
- Battery degradation factor → In (Beer, et al., 2012) there are two degradation factors defined; Vehicle to grid: when the flow goes directly from the battery to the grid or viceversa; and Driving degradation factor: when the energy from the battery is used for driving.
    - V2G factor: 0,0027 %
    - Driving factor: 0,006 %

Matematical formulation in the model: following (Beer, et al., 2012)

$$\sum_{hr} ReplaceCost * \frac{V2Gdegfactor * V2Gflow + Drivedegfactor * Drivingcons}{1 - EOL}$$

Being:

- $V2Gdegfactor = 0{,}000027\ pu\ PARAMETER$
- $Drivedegfactor = 0{,}00006\ pu\ PARAMETER$
- $ReplaceCost = 230\,\frac{€}{kWh}\ according\ to$ $\text{(McKinsey\&Company, Jan 2017)}$ $PARAMETER$
- $EOL = 0{,}8\ PARAMETER$
- $V2Gflow\ and\ Drivingcons\ are\ VARIABLES\ from\ the\ model$

III. ROM Model

ROM is the acronym for *Reliability and Operation Model*, it is used in the IIT for the research on the impact of Renewable Energy Sources in the power system. Because of this, it is found suitable for the analysis that this thesis pretends to seek. This model also allows to consider different distributed energy sources, from solar PV generation to batteries.

Within the distributed energy sources that it allows to model one of them are battery electric vehicles. The model allows to simulate the characteristics of various types of EVs with different technical characteristics, different connection hours to the grid or different distance range per day between others.

In the next figure, the main modelling characteristics of EV type used are presented. For the sake of simulation time only one type of EV has been considered but if more types are to be included the model allows to model each type individually.

	Energy [kWh]	**Min Energy** [p.u.]	**Max Energy** [p.u.]	**GTB**[3] **Efficiency** [p.u.]	**BTW**[4] **Efficiency** [p.u.]	**BTG**[5] **Efficiency** [p.u.]	**Charging Ramp** [kW/h]	**Discharging Ramp** [kW/h]	**Maximum Output** [kW]
	Energy	**MinEnergy**	**MaxEnergy**	**GTBEff**	**BTWEff**	**BTGEff**	**ChargeRate**	**DischrRate**	**MaxBEVOut**
BEV001	28	0,20	0,95	0,95	0,95	0,95	3,0	3,0	3,0

Table 1: BEV characteristics used in this thesis.

In

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[3] Grid to battery efficiency. Accounts for the efficiency when the energy flow goes from the frid to the electric vehicle battery

[4] Battery to Wheel efficiency. Account for the efficiency of the Flow of energy from the battery to the wheels.

[5] Battery to grid. Accounts for the efficiency of the energy flow when delivering energy to the grid.

Annex I, the percentage of distance covered in that hour and the number of EVs plugged to the grid is shown. There are 2 different uses given to the EVs, number 1 which is during weekdays and number 2 which is for weekends.

These 2 factors are important when analyzing the results of the model because despite that prices are the most important factor for the charging and discharging of EVs if there are no connected cars to the grid it is impossible to consume or deliver energy to the grid.

Solar PV generation is modeled as local generation in each node of the system while batteries and EVs, because of the current structure of the model, can only be included in what is going to be called the "Aggregators node". In this thesis, the only distributed energy source used are going to be the EVs, but future work can be done including solar generation and/or batteries to assess the benefits that can come from managing in parallel solar generation, batteries and EVs.

A good description of the model is given in (Castro Cerdas, 2016). "The ROM is a unit commitment and economic dispatch model that includes a series of inputs as generation units' characteristics, load profile, reliability parameters, and another series of parameters that represent the electric network characteristics. On the other hand, the main outputs of the model are the hourly operation of the generation units, Carbon dioxide (CO_2) emissions, prices, and grid related outputs like power flows". The generation units are modelled in detail with its main technical characteristics like O&M costs, fuel usage, start-up…

In Figure 8 the main outputs and inputs of the model can be seen:

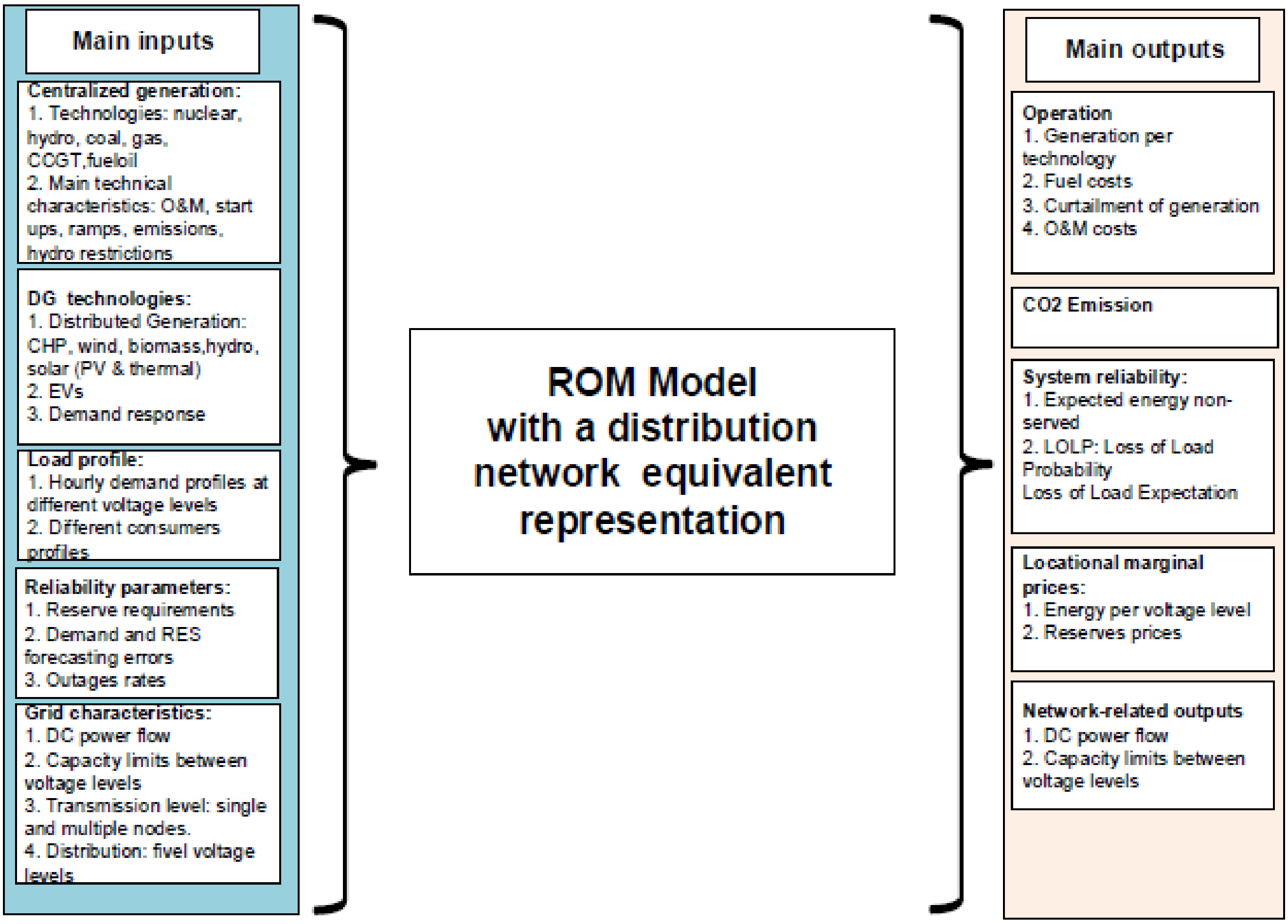


Figure 8: ROM inputs and outputs. Source: (Castro Cerdas, 2016).

The grid representation of the Model is important for the purpose of this thesis since it allows to calculate Locational Marginal Prices (LMP), this is thanks to the different nodes that form the model, each node is chosen according to the demand and the voltage level it is connected to. Under this model, a different marginal price is obtained for each network node, and demand pays the marginal price corresponding to its node, while generation receives the marginal price of its node as well.

The ROM solves a daily optimization for a whole year, and simulates the real-time operation for each day.

Figure 9 presents a graphical representation of the grid modelling in ROM.

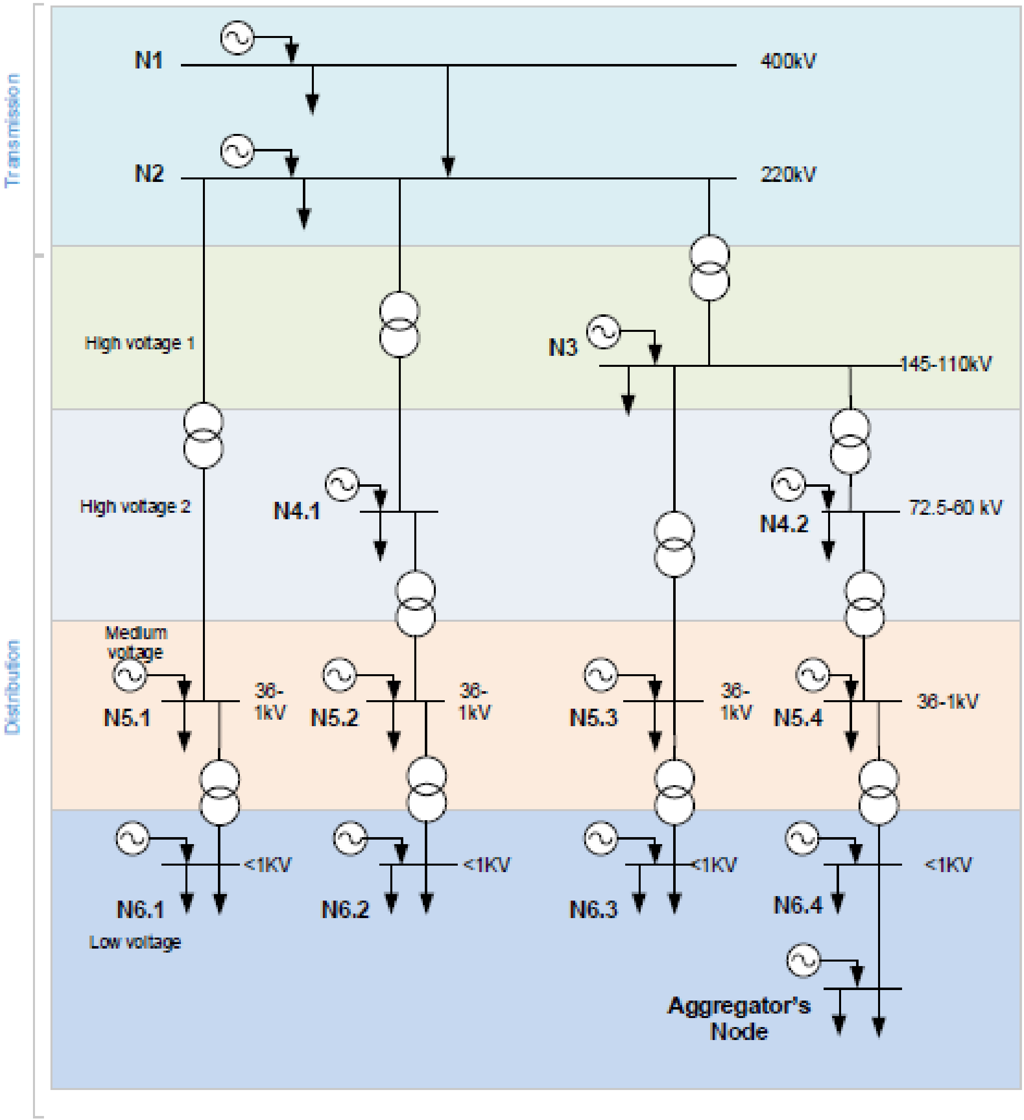


Figure 9: Simplified grid representation of the ROM. Figure from (Castro Cerdas, 2016).

In the aggregator node, we will only consider the presence of Electric Vehicles, as it has been said throughout the text of the thesis. Although in this case the objective is analyzing the behavior and effects of the EVs; solar generation and demand can also be included in the aggregators node. This allows to consider the operation modes of distributed energy resources.

IV. Definition of case studies

As it has been exposed in previous sections the main objective of this thesis is to study the impact and the benefits that can be extracted from the aggregation of EVs in the power system. That is why ROM has been chosen, it has a schematic representation of the Spanish grid and allows to study different marginal prices modelling and regulated tariffs.

In this sense, the case studies are going to be defined by those two elements: marginal pricing scheme and tariff implemented. Therefore, 4 case studies are going to be proposed according to the different tariff and pricing schemes.

1. Tariff designs: Spanish tariff and an Efficient tariff according to (Castro Cerdas, 2016).
2. Energy pricing: Single price node and Locational Marginal Prices.

A. Tariff designs

There are two tariffs considered:

1. Spanish tariff

The purpose of this tariff is to promote the charging of EVs at valley demand hours and to penalize the EV charging at peak hours. That is why in the Spanish tariff for Electric Vehicles there are 3 differentiated time zones: valley, flat and peak. In Figure 10 a profile of how the tariff is applied is shown.

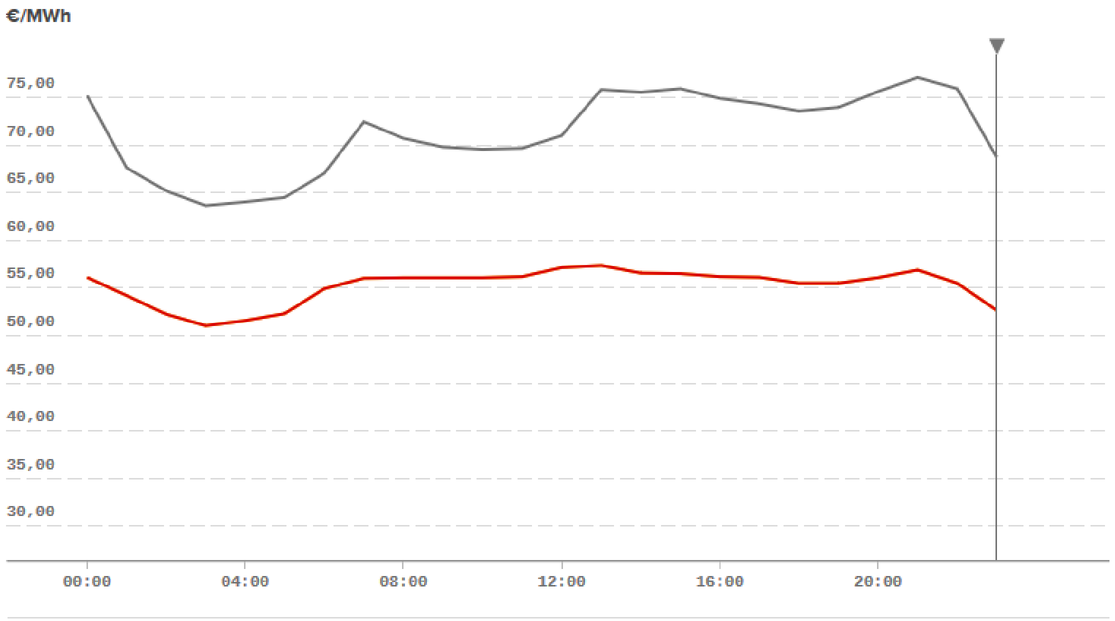


Figure 10: EV tariff vs the wholesale spot price in Spain. Red is the spot price in Spain for 1/June/2017 and grey is the EV tariff applied to consumers. Graph from Esios (REE).

As it can be seen, there are 3 clear periods and the EV tariff does not follow the same profile as the spot price because regulated costs are passed from low price hours to higher price hours.

Another characteristic of the Spanish tariff is that network and other regulated costs are also charged via maximum power contracted. This has also been modelled.

2. Modelling of the Spanish tariff

One of the differences between this thesis and (Castro Cerdas, 2016) is in how the Spanish tariff is modelled. In Castro Cerdas (2016) the network costs are charged to the 40% of the highest flows between the system and the aggregators node. In reality, the Spanish tariff is charged at every hour for the amount of the contracted capacity as it has been mentioned above.

To do this the next formulation has been implemented, but because of the structure of the model it was not possible to charge the maximum demand of the entire year for every hour so a simplification had to be made. Since the simulation goes day by day the demand to be charged is the maximum of the day before and being this one greater than the precedent.

$$\textit{Maximum demand from the aggregators node saved until the moment} \rightarrow pDemandMax$$

$$\textit{Variable where the maximum demand of each day is obtained to compare with } pDemandMax \rightarrow vDemandMax$$

$$\textit{This term is added to the cost function in ROM}:$$

$$\sum_{hour,day} \left(NetworkCharge\left[\frac{€}{MWh}\right] * Flow_{system_{\rightarrow aggregator}} + vDemandMax * NetworkCharge\left[\frac{€}{kW}\right] \right)$$

$$\textit{Two restrictions are added in order to calculate de maximum demand for the network charges}:$$

$$vDemandMax \geq pDemandMax$$

$$\textit{so that the parameter is always the maximum demand registered in the simulation.}$$

$$vDemandMax \geq Flow_{system_{\rightarrow aggregator}}$$

$$\textit{So that the maximum demand registered is always higher than the demand recorded in the simulated day}$$

3. Efficient network tariff.

This tariff, explained in (Castro Cerdas, 2016) charges the network costs in two ways, 20% of the costs (representing incremental network costs) in the form of a peak demand charge and the 80% as a fixed charge. This implementation is done exclusively to the aggregator's node, while the cost allocation for the remaining nodes of the system persists as a fixed charge.

As for peak demand charge, a peak threshold has to be defined in order to know which hours are going to be charged with the peak demand charge.

For the application of this tariff the same steps as in (Castro Cerdas, 2016) are going to be applied.

B. Methodology

The methodology followed in this thesis is basically to compare results between case studies. The reference case study of this thesis is the one in which the Spanish tariff is applied with a single node pricing scheme. In order to compare the tariffs implementation and effects a case study without any tariff is made, this is only a unit commitment problem.

The ultimate case study of this thesis is the application of the efficient tariff along with a LMP pricing, but as it is not seen as for possible immediate implementation another case study is done to catch a possible transition effect. The one considered most viable is the one where the single price scheme is still in place but with the efficient tariff applied to recover regulated costs.

The main results that are going to be analyzed in the case studies are the system and thermal generation costs, losses in the system, marginal prices, EVs behavior, CO2 emissions and non-served energy if it appears.

The objective is to search whether there are more benefits that can be extracted from the current tariff and system applied in Spain or from the possible implementation of a tariff considered as more efficient and if these benefits are promoted by implementing a single price scheme or LMPs perform better.

C. Input data

1. Demand

The demand is taken from a study for the year 2025 for Greenpeace made by the IIT, (IIT, 2017) where the same ROM model was used.

For the projection of future demand the main variable considered is the gross domestic product although energy efficiency measures are altering the original relationship between the GDP and the electricity demand. The next table shows the projections employed in the study for future GDP evolution.

	MINECO	OECD

2016	3,2%	2,4%
2017	2,7%	2,2%
2018	2,5%	1,9%
2019	2,4%	1,7%
2020	2,4%	1,6%
2021		1,6%
2022		1,7%
2023		1,7%
2024		1,8%
2025		1,9%

Table 2: Future projections made for the Spanish GDP by the Ministry of Economy, Industry and Competitiveness and the OECD. Table from (IIT, 2017).

These projections are used to calculate the demand evolution of the different sectors in the study, the sectors taken into account in (IIT, 2017) are: industrial sector, services sector, residential sector, EV demand (although in this thesis the projection used is the one from (Ministerio de Industria, Energía y Turismo, June 2015)) and international interconnection.

Each of the demand sectors has its own projection of the demand evolution and how the efficiency improvement affects each one of them.

2. Electric Vehicles

Ministerio de Industria, Energía y Turismo (Junio 2015) makes an estimation that in 2020, the number of EVs in the Spanish system will be of 150.000, this will be the number that will be used in the simulations and seems a good number to assess the impact in the system. Logically, for a higher number of EVs the impact in the system increases since there will be more demand and more storage available.

In (IIT, 2017) there is another number proposed for 2020, 500.00 Electric Vehicles. But since this thesis is following the one Catro-Cerdas made a year ago the number used is 150.000 EVs.

3. Renewable generation

The renewable generation installed capacity is taken from the same study cited for the demand data. Predictability renewable generation errors are considered in the ROM model, but no stochasticity is taken into account. Future generation scenarios are considered based on (IIT, 2017) for Greenpeace study. The average hourly generation profiles for each technology is considered based on historical data from 2012 to 2016.

The future renewable generation installed capacity is in line with future scenarios where decarbonization objectives are reached.

V. Results

A. No tariff, Locational Marginal Prices. Reference case.

In this case study, there is a total demand of 286.726.459 MWh (287 TWh) from which 498.272 MWh are from the Electric Vehicles. The energy that EVs introduce into the system is 6.693,24 MWh, only the 1,3% of the EV demand. This is shown in Table 3.

	Demand	EV Demand	EV Generation
MWh	286.726.460	498.273	6.693
% of demand		0,174%	0,002%

Table 3: Demand and EV generation and consumption for no tariff simulation.

1. Thermal generation costs

The thermal generation costs for the system account to 4.326,392 M€.

2. Losses in the system

The total losses in the system are a 5,15% of the system demand, a total of 14.770.007,30 MWh in losses.

3. Marginal prices

	Mg_Pr [€/MWh]		Mg_Pr [€/MWh]
NODE_1	38,928	NODE_5_3	42,576
NODE_2	39,617	NODE_5_4	43,500
NODE_3	41,866	NODE_6_1	41,893
NODE_4_1	40,337	NODE_6_2	43,482
NODE_4_2	42,674	NODE_6_3	44,947
NODE_5_1	40,143	NODE_6_4	46,286
NODE_5_2	41,073	NODE_7_4	46,287

Table 4: Average marginal prices per node.

As it can be seen from Table 4 (see Figure 9 to locate these nodes in the system) the prices increase from higher voltage levels (i.e. transmission) to lower voltage levels (i.e. distribution), which confirms us that prices increase as energy losses increase and that the marginal prices are being set correctly. That is due to the losses effect, since most of the generation is located on Node 1 at transmission and the demand is divided over the different nodes of the system at distribution.

The model also allows us to see how the marginal prices change hour by hour each day of the year. For the purpose of saving space, in Table 5 the average hourly prices for the whole year are shown. A color format is added so see more visually the pattern of hourly prices.

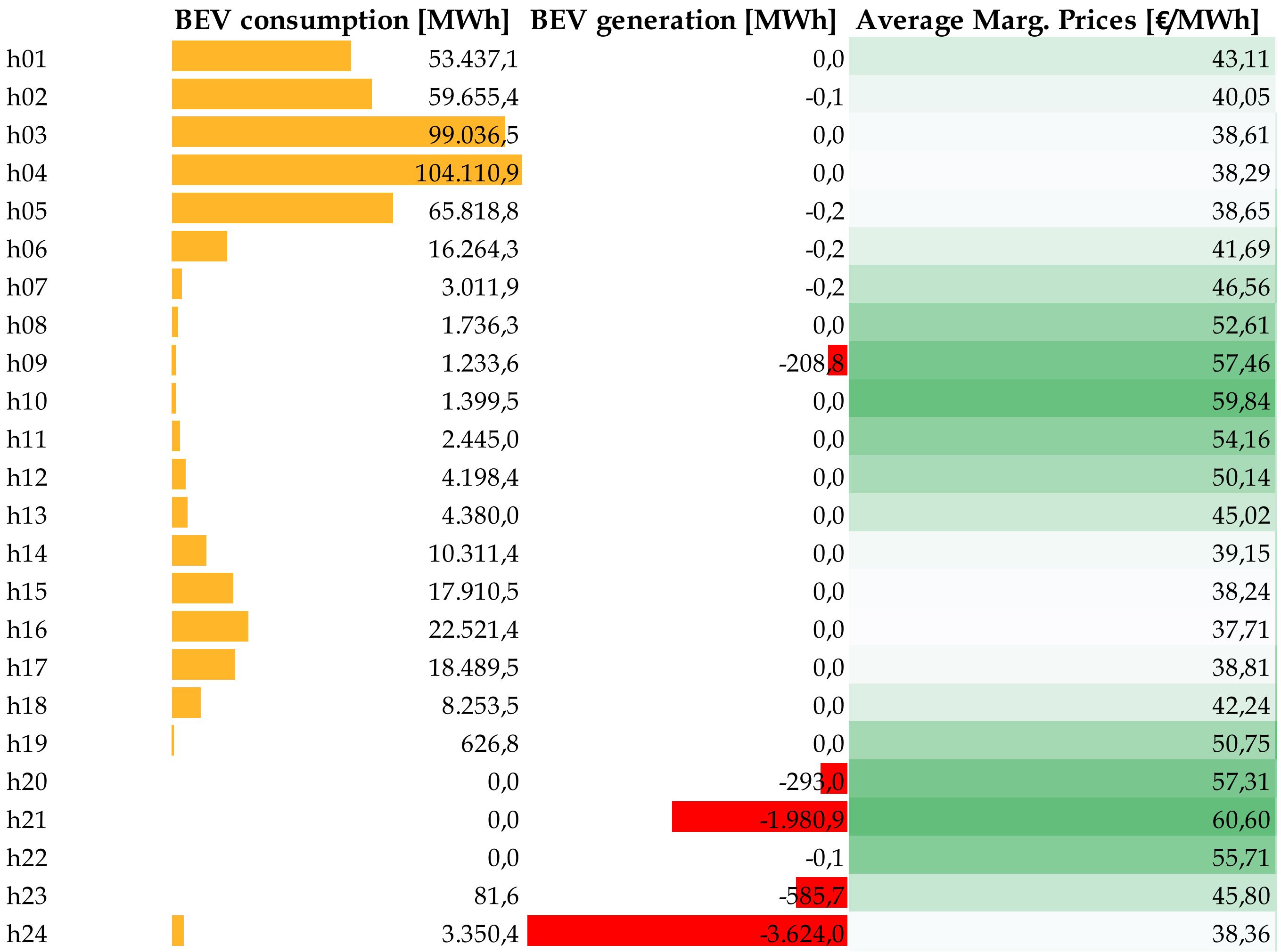
	Average Marg. Prices [€/MWh]
h01	43,11
h02	40,05
h03	38,61
h04	38,29
h05	38,65
h06	41,69
h07	46,56
h08	52,61
h09	57,46
h10	59,84
h11	54,16
h12	50,14
h13	45,02
h14	39,15
h15	38,24
h16	37,71
h17	38,81
h18	42,24
h19	50,75
h20	57,31
h21	60,60
h22	55,71
h23	45,80
h24	38,36

Table 5: Average hourly marginal prices. No tariff simulation.

As it can be seen, prices behave as nowadays, there is a first peak before mid-day and there is another peak at 9 PM when, most commonly, people start having dinner and TVs get turned on.

4. Electric Vehicle behavior

According to the results extracted from the simulation, the next table summarizes the average hourly behavior of EV charging (BEV consumption) and EV injecting energy to the grid (BEV generation) for the entire year. The following table shows the results.



	BEV consumption [MWh]	BEV generation [MWh]	Average Marg. Prices [€/MWh]
h01	53.437,1	0,0	43,11
h02	59.655,4	-0,1	40,05
h03	99.036,5	0,0	38,61
h04	104.110,9	0,0	38,29
h05	65.818,8	-0,2	38,65
h06	16.264,3	-0,2	41,69
h07	3.011,9	-0,2	46,56
h08	1.736,3	0,0	52,61
h09	1.233,6	-208,8	57,46
h10	1.399,5	0,0	59,84
h11	2.445,0	0,0	54,16
h12	4.198,4	0,0	50,14
h13	4.380,0	0,0	45,02
h14	10.311,4	0,0	39,15
h15	17.910,5	0,0	38,24
h16	22.521,4	0,0	37,71
h17	18.489,5	0,0	38,81
h18	8.253,5	0,0	42,24
h19	626,8	0,0	50,75
h20	0,0	-293,0	57,31
h21	0,0	-1.980,9	60,60
h22	0,0	-0,1	55,71
h23	81,6	-585,7	45,80
h24	3.350,4	-3.624,0	38,36

Table 6: BEV hourly average consumption and generation vs hourly average marginal prices. No Tariff simulation.

From Table 6 it can be observed that EVs consume more energy in the cheapest hours as it seems logical at first, there is great correlation between consumption hours and low-price hours. Following the logic, EVs deliver electricity to the grid when prices are sufficiently high to compensate for the consumption, storage and the battery and energy losses associated. Because of the losses and battery degradation modelled, EVs are not willing to deliver much electricity to the grid (a 0,002% of the system total energy demand, value can be seen in Table 3), this is because of the low volatility of prices, there are not many hours with Marginal Prices over 80 €/MWh. In total, there are only 565 hours with prices over 80 €/MWh.

It may seem strange that in a cheap hour as it is midnight, there is a lot of generation compared to the rest of hours. There is no logical explanation to this fact, the only explanation found is in how the model is structured, since it is a unit commitment model for the entire year and with 14 nodes, the simulation is done day by day simulating the market scheduling. In this sense, EVs have a restriction to have a certain amount of energy at midnight, which could distort the results of the simulation. In any case, the other patterns found for consumption and generation seem logical and are considered valid.

Another question is done looking at the behavior of EVs; why do they deliver more energy to the grid at night even if the prices at those hours are lower?

During the day, all the energy withdrawn for the grid is used for the transportation, and since the batteries have a limited capacity the cars cannot generate if afterwards it's not going to have energy for the km travelled. That is why most of the returning energy to the grid is done at night, most of the cars are connected to the grid because people have parked their cars when they got home and there is no more use for transport done with the car in that day.

5. Emissions

There are 43,76 Mt CO_2 emitted by the generation units.

6. Non-served energy

There is no non-served energy in this simulation.

B. Spanish tariff, single node price.

In this case study, the total demand of the system including losses accounted for a total of 285.464.454 MWh coming a 0,157% from the EVs (447.351 MWh EV demand). Generation from EVs only accounted for a total of 4.405 MWh, a 0,002% of the total demand.

In the next table these results are summarized:

	Demand	BEV consumption	BEV generation
MWh	285.464.454	447.351	4.405
% of demand		0,157%	0,002%

Table 7: Demand and EV behavior for the study with the Spanish tariff and single node pricing.

1. Thermal generation costs

For this case study, thermal generation costs account for a total amount of 4.350,903 M€.

2. Losses in the system

Losses decrease compared with the reference case study due to the lower demand and flows. Next table shows the total of losses and its percentage of the demand.

	Demand	Losses
MWh	285.464.454	14.621.709
% of demand		5,122%

Table 8: Losses for the Spanish tariff with single pricing scheme.

3. Marginal prices

	Average Marg. Prices [€/MWh]
h01	37,7
h02	37,4
h03	37,1
h04	36,8
h05	37,4
h06	39,8
h07	44,5
h08	50,3
h09	52,4
h10	52,6
h11	47,4
h12	43,8
h13	40,0
h14	36,7
h15	36,2
h16	36,2
h17	37,6
h18	41,4
h19	46,4
h20	50,5
h21	51,0
h22	50,0
h23	42,7
h24	36,0

Table 9: Average hourly marginal prices for the Spanish tariff with single pricing scheme simulation.

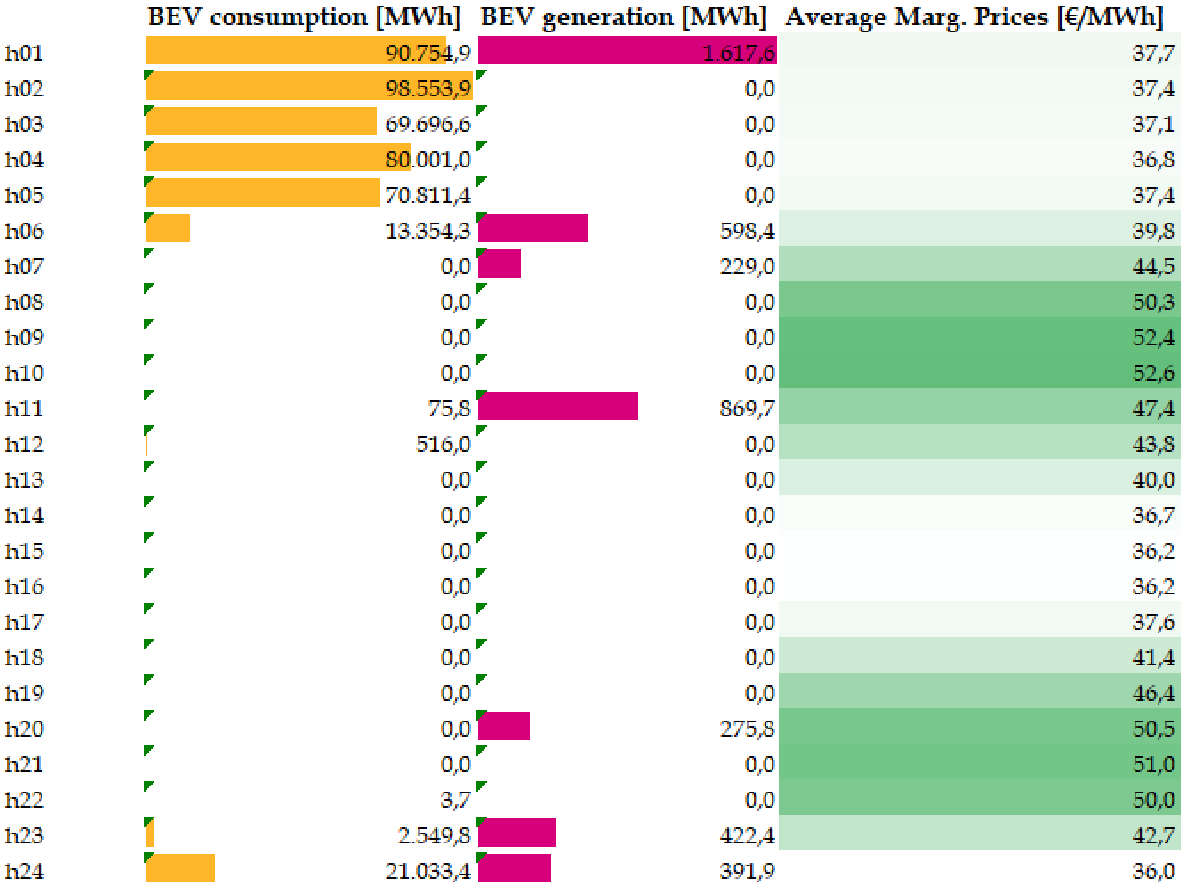
As it can be seen from Table 9 prices keep on having the same profile as in the precedent simulations. Peak hours are around 10 AM and 9 PM.

Another idea that can be concluded from the tables with the results of the average hourly prices and comparing with **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.** is that the low price hours from 13 PM to 18 PM can be due to the little amount of vehicles connected to the grid and how much of the daily distance is covered in those hours, this is why BEV consumption never peaks in these hours.

4. Electric Vehicle behavior

There is a not wide spread in marginal prices between hours for this simulation (standard deviation of 11,53 lower than std. dev. of 25,2 for the efficient tariff with LMP), that is why the total generation of EVs is lower than in the rest of the simulations. There is not enough spread to compensate for the degradation effect and the efficiencies lost in consuming and delivering energy.

In Table 10 the hourly behavior of EVs is shown with the average marginal prices for each hour.



	BEV consumption [MWh]	BEV generation [MWh]	Average Marg. Prices [€/MWh]
h01	90.754,9	1.617,6	37,7
h02	98.553,9	0,0	37,4
h03	69.696,6	0,0	37,1
h04	80.001,0	0,0	36,8
h05	70.811,4	0,0	37,4
h06	13.354,3	598,4	39,8
h07	0,0	229,0	44,5
h08	0,0	0,0	50,3
h09	0,0	0,0	52,4
h10	0,0	0,0	52,6
h11	75,8	869,7	47,4
h12	516,0	0,0	43,8
h13	0,0	0,0	40,0
h14	0,0	0,0	36,7
h15	0,0	0,0	36,2
h16	0,0	0,0	36,2
h17	0,0	0,0	37,6
h18	0,0	0,0	41,4
h19	0,0	0,0	46,4
h20	0,0	275,8	50,5
h21	0,0	0,0	51,0
h22	3,7	0,0	50,0
h23	2.549,8	422,4	42,7
h24	21.033,4	391,9	36,0

Table 10: EV behavior compared with the average marginal prices for each hour. Spanish tariff with single node price.

As it can be seen from Table 10 the first and last hour of the day concentrate a great quantity of energy consumed and delivered to the grid from EVs. This has to do with the structure of the model as mentioned before about the distortion that the midnight energy restriction creates in the model. There are other factors that affects the hours in which there is energy delivered from EVs, and that is the hours in which energy is used for transport and the number of plugged cars in the grid in every hour, these two parameters can be seen in

Annex I.

Comparing Table 10 and Table 6 another clear distortion can be observed, the Spanish tariff clearly accomplishes its objective of promoting the charging of EVs during the night hours but the high tariff prices passed to the rest of the hours of the day do not allow users to have sufficient flexibility to store energy and inject energy back to the grid. This fact, added to lower prices and a lower spread of prices because of the lower demand, creates a situation in which there is no incentive to store, to later on give back to the grid.

5. Emissions

With this tariff applied, the emissions decrease a 9%, almost the same fall that the EV demand has (a 9,89%). Emissions account for a total of 39,84 Mt CO_2.

6. Non-served energy

There is no non-served energy in this simulation.

C. Efficient tariff, single node price

The total demand of the system for the entire year, total electric vehicle´s consumption and the energy delivered back to the grid is summarized in the following table:

	Demand	BEV consumption [MWh]	BEV generation [MWh]
MWh	286.238.446	526.531	32.196
% of demand		0,184%	0,011%

Table 11: Demand and BEV behavior for the efficient tariff with single node pricing.

There is not a big change on demand from the rest of simulations, but compared to the simulation with efficient tariff and nodal price electric vehicles decrease substantially their demand and generation back to the grid. Demand from EV decreases around a 9%, but generation from EVs seems clearly penalized from a single node pricing, it decreases its overall generation in 58%.

1. Thermal generation costs

Thermal generation costs account for a total of 4.136,5 M€.

2. Losses in the system

Losses increase to a total of 15.037.616 MWh, a 5,25% of the demand. Higher than in the nodal pricing scheme case study.

3. Marginal prices

As it can be seen on the following table, marginal prices keep the same profile as in the rest of the case studies and have a higher spread than in the Spanish case tariff but a lower spread than the efficient tariff with a nodal scheme. The standard deviation is 21, for a 25 in the nodal pricing scheme case study and a 11,5 for the Spanish case study.

	Average Marg. Prices [€/MWh]
h01	35,43
h02	34,26
h03	33,32
h04	33,41
h05	33,33
h06	35,58
h07	39,05
h08	43,22
h09	43,90
h10	44,19
h11	38,35
h12	36,20
h13	34,08
h14	30,33
h15	29,00
h16	29,44
h17	29,73
h18	32,61
h19	36,29
h20	39,54
h21	37,59
h22	34,12
h23	31,12
h24	24,99

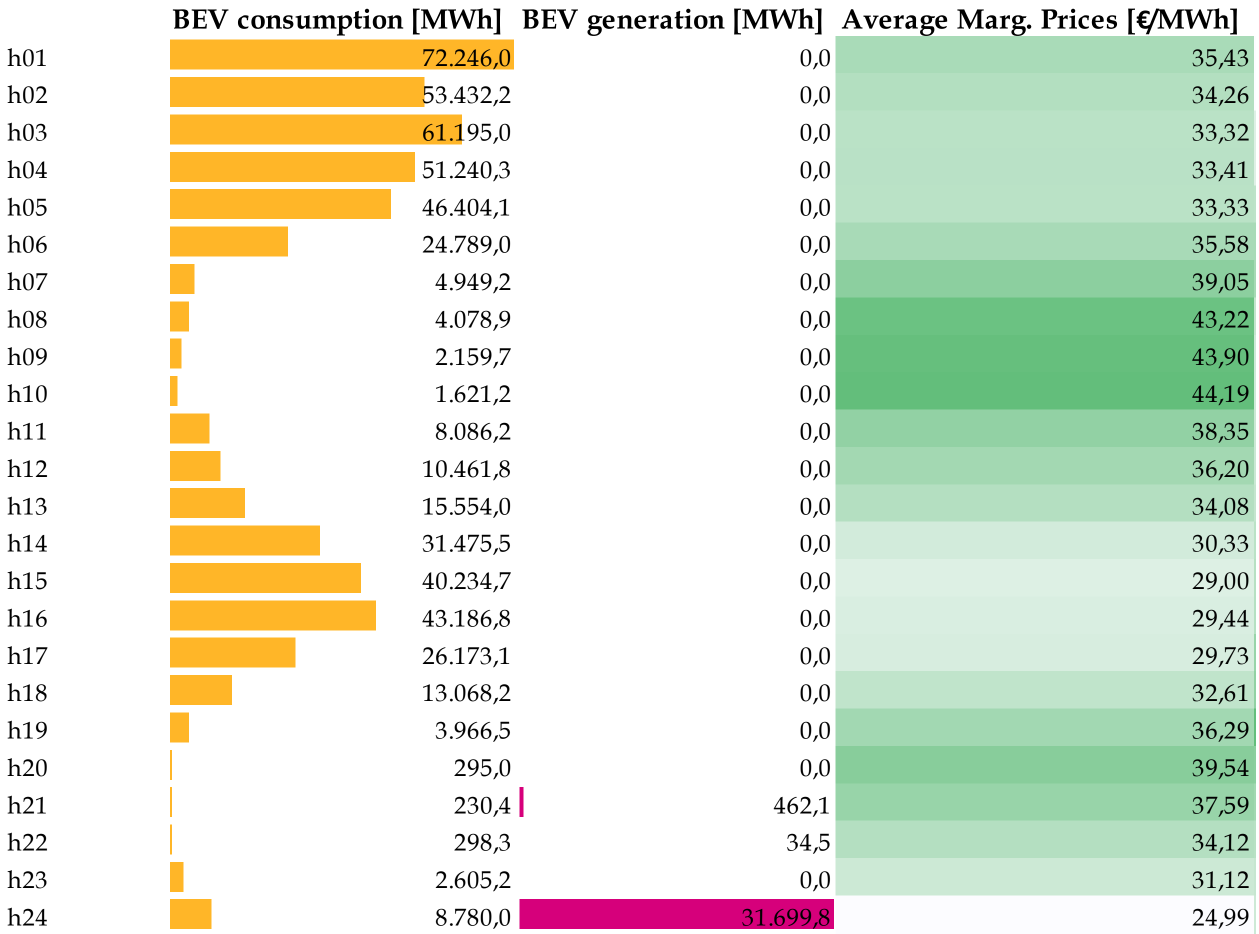
Table 12: Average hourly marginal prices. Efficient tariff with single node pricing.

4. Electric Vehicle behavior

In the following table, the average consumption and generation from EVs is presented.

As it can be observed, there is a high distortion due to the midnight energy restriction for EVs since more than 90% of the energy delivered back to the grid comes at midnight.

The distortion affects much more the generation data than the consumption data. As it can be seen from the first column the demand corresponds to the hours where the prices are lower, except at 1 AM where the distortion makes it the hour with the highest demand but with not the lowest price.



	BEV consumption [MWh]	BEV generation [MWh]	Average Marg. Prices [€/MWh]
h01	72.246,0	0,0	35,43
h02	53.432,2	0,0	34,26
h03	61.195,0	0,0	33,32
h04	51.240,3	0,0	33,41
h05	46.404,1	0,0	33,33
h06	24.789,0	0,0	35,58
h07	4.949,2	0,0	39,05
h08	4.078,9	0,0	43,22
h09	2.159,7	0,0	43,90
h10	1.621,2	0,0	44,19
h11	8.086,2	0,0	38,35
h12	10.461,8	0,0	36,20
h13	15.554,0	0,0	34,08
h14	31.475,5	0,0	30,33
h15	40.234,7	0,0	29,00
h16	43.186,8	0,0	29,44
h17	26.173,1	0,0	29,73
h18	13.068,2	0,0	32,61
h19	3.966,5	0,0	36,29
h20	295,0	0,0	39,54
h21	230,4	462,1	37,59
h22	298,3	34,5	34,12
h23	2.605,2	0,0	31,12
h24	8.780,0	31.699,8	24,99

Table 13: Average EV consumption and generation for every hour of the day. Efficient tariff with single node pricing.

The distortion causes a deep decrease of the price at midnight making it the hour with the highest generation and lowest price.

It's relevant that the consumption pattern is maintained compared to the efficient tariff with nodal pricing, which is coming next, the EVs try to consume in the hours with lower price independently of how many are connected to the grid.

5. Emissions

Emissions in this case study account for a total of 44,6 Mt CO_2.

6. Non-served energy

There is no non-served energy in this case study.

D. Efficient tariff, Locational Marginal Prices

In this simulation, the considered as efficient tariff in (Castro Cerdas, 2016) is implemented and the pricing scheme applied is a LMP, the total demand of the system, including losses, the consumption of EVs and its generation are shown in Table 14.

	Demand	EV Demand	EV Generation
MWh	286.794.953	575.815	76.675
% of demand		0,201%	0,027%

Table 14: System demand and EVs generation and consumption. Efficient tariff with LMP.

From comparing with Table 3 from the reference case, we can see that net demand increases in a 0,0024%, this is almost nothing, this is because EVs have the same transportation consumption but withdraw more energy from the grid to take advantage of higher prices later. This is proved in Table 14, EV consumption is higher than in the reference case, the same happens for generation. The net consumption is almost the same for EVs in both simulations, which would be the energy used for transportation.

1. Thermal generation costs

The thermal generation costs for this simulation increases compared to the reference case with no tariff applied accounting for a total of 4.350,903 M€.

2. Losses in the system

Losses also increase compared to the reference case with no tariff, this is due to the fact of the increasing EV consumption. Losses account for a 5,22% of the total energy demand, this is 14.978.426,55 M€.

3. Marginal prices

As in the reference case, this simulation applies a LMP pricing scheme, therefore, each node has a different price, but as it can be seen in Table 15 the increase in price goes from upstream to downstream, which has theoretical sense because generation is upstream and the capacity limits of the lines and losses create a difference of prices.

	Mg_Pr [€/MWh]		**Mg_Pr [€/MWh]**
NODE_1	39,561	NODE_5_3	42,733
NODE_2	39,887	NODE_5_4	43,662
NODE_3	42,019	NODE_6_1	42,181
NODE_4_1	40,612	NODE_6_2	43,805
NODE_4_2	42,832	NODE_6_3	45,123
NODE_5_1	40,417	NODE_6_4	46,468
NODE_5_2	41,354	NODE_7_4	46,468

Table 15: Average yearly marginal prices for each node of the system. Efficient tariff with LMP.

From the simulation, marginal hourly prices are obtained for the aggregators node, this can be seen in Table 16.

The peak hours are not changed, as in the case with no tariff applied, the peak hours are at 10 AM and at 9 PM. But, the average price is increased from 46,29 €/MWh to 46,5 €/MWh, this is because of the higher demand from EVs.

From Table 16 and comparing it with Table 5 the demand profile is maintained, of course, this was expected since EVs are not a great part of the demand. In this case, EVs account for a 0,201% of the total energy demand.

	Average Marg. Prices [€/MWh]
h01	44,1
h02	39,3
h03	38,3
h04	38,3
h05	38,7
h06	41,5
h07	47,0
h08	52,9
h09	57,4
h10	60,7
h11	54,0
h12	50,1
h13	46,3
h14	39,4
h15	38,3
h16	37,8
h17	39,5
h18	42,5
h19	51,2
h20	57,0
h21	61,7
h22	56,4
h23	45,4
h24	37,3

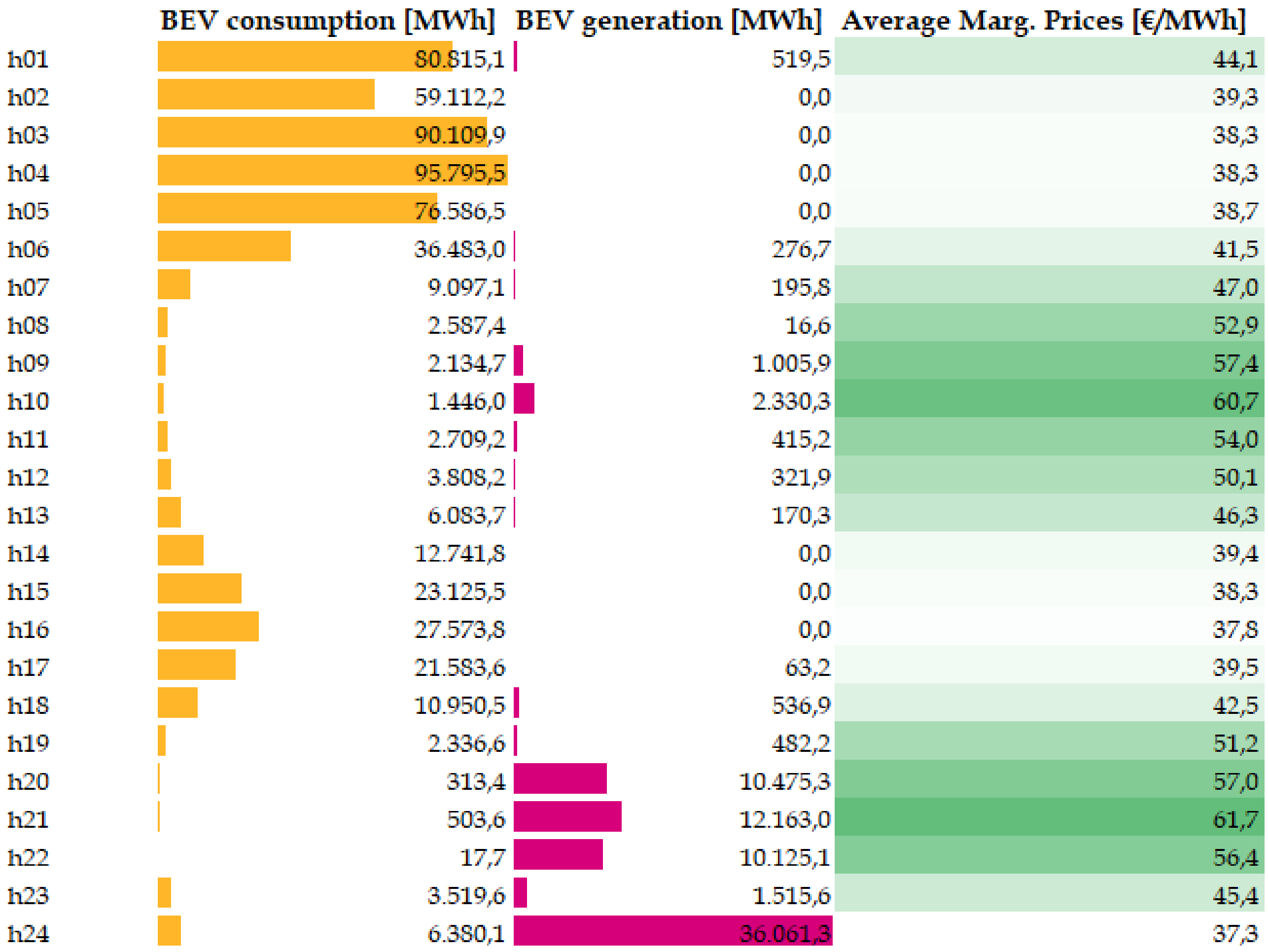
Table 16: Average yearly marginal prices for each hour of the day in the aggregators node. Efficient tariff with LMP.

4. Electric Vehicle behavior

As shown in Table 14, EV demand accounts for a 0,201% of the demand and the energy returned from the EVs to the grid accounts for a 0,027% of the demand, both factors have increased compared to the case without tariff. The net demand of EVs is 499.139,94 MWh.

As it happens in the No tariff case, consumption is concentrated in those hours in which the price is lower. Again, there is a high distortion in the generation and consumption patterns due to the energy restriction at midnight, for this reason most of the energy generated is returned to the grid at midnight. Despite this, the pattern shows that for high price hours, energy is returned to the grid if sufficiently high. There is a 0,65 correlation coefficient between the generation of EVs and the high price hours and a 0,68 correlation between the high price hours and the consumption hours.

In the following table, the data regarding EV behavior is shown.



	BEV consumption [MWh]	BEV generation [MWh]	Average Marg. Prices [€/MWh]
h01	80.815,1	519,5	44,1
h02	59.112,2	0,0	39,3
h03	90.109,9	0,0	38,3
h04	95.795,5	0,0	38,3
h05	76.586,5	0,0	38,7
h06	36.483,0	276,7	41,5
h07	9.097,1	195,8	47,0
h08	2.587,4	16,6	52,9
h09	2.134,7	1.005,9	57,4
h10	1.446,0	2.330,3	60,7
h11	2.709,2	415,2	54,0
h12	3.808,2	321,9	50,1
h13	6.083,7	170,3	46,3
h14	12.741,8	0,0	39,4
h15	23.125,5	0,0	38,3
h16	27.573,8	0,0	37,8
h17	21.583,6	63,2	39,5
h18	10.950,5	536,9	42,5
h19	2.336,6	482,2	51,2
h20	313,4	10.475,3	57,0
h21	503,6	12.163,0	61,7
h22	17,7	10.125,1	56,4
h23	3.519,6	1.515,6	45,4
h24	6.380,1	36.061,3	37,3

Table 17: EV behavior and pattern. Efficient tariff with LMP.

5. Emissions

As exposed before, thermal costs increase because of the demand increase, the emissions also increase with respect to the no tariff case. In this case emissions go up to 44,210 Mt CO_2, a 1,02% over the no tariff case. The emission increase for this case study is due to the production of CCGTs and Coal plants. CCGTs increase its production in a 0,56% and Coal units in a 1,16%.

6. Non-served energy

There is no non-served energy in this simulation.

E. Reference case with no tariff and no degradation modelling, LMP pricing.

For this case study, the modeling of the degradation of batteries due to the energy flows is eliminated to assess the impact in the results of this new effect added to the model.

The demand and the EV consumption and generation are shown in Table 18:

	Demand	BEV consumption [MWh]	BEV generation [MWh]
MWh	286.825.040	618.267	113.003
% of demand		0,216%	0,039%

Table 18: System demand and EV generation and consumption for the simulation with no degradation effect.

The demand increases compared to the reference case due to the increase in EV consumption.

1. Thermal generation costs

For this case study, thermal generation costs account for a total amount of 4.322,838 M€.

2. Losses in the system

The energy losses in the system are 14.912.405 MWh. Higher than in the reference case with degradation due to a higher demand from EVs.

3. Marginal prices

Taking a look at the last row of Table 19 we can see that the average from the no degradation simulation is much lower. This represents the change in price that vehicles have to compensate when taking into account the capacity losses because of the degradation effect that the batteries suffer.

Average Marg. Prices [€/MWh]	**No degradation**	**With degradation**
h01	38,8	43,1
h02	38,0	40,1
h03	36,7	38,6
h04	36,5	38,3
h05	36,6	38,7
h06	38,0	41,7
h07	40,1	46,6
h08	41,9	52,6
h09	42,7	57,5
h10	43,3	59,8
h11	41,9	54,2
h12	40,7	50,1
h13	39,9	45,0
h14	37,5	39,2
h15	36,5	38,2
h16	36,0	37,7
h17	37,1	38,8
h18	39,0	42,2
h19	40,9	50,8
h20	42,7	57,3
h21	42,7	60,6
h22	42,0	55,7
h23	39,7	45,8
h24	37,3	38,4
Average	***39,4***	***46,3***

Table 19: Comparison between marginal prices from the reference case with degradation and no degradation modelled.

The shape of the profile doesn’t change, so the peaks keep on being in the same hours, around 10 AM and 9 PM, and so do the valley hours. Also, prices have a lower volatility when the degradation effect is not modelled.

4. Electric Vehicle behavior

Since there is no degradation effect and volatility keeps up at a level similar to the case study with a degradation effect, the generation of the EVs shoots up, giving back to the grid around 113.000 MWh, which compared to the 6.700 MWh from the reference case with degradation gives an idea of the higher flexibility that vehicles could have if the degradation effects were lowered significantly.

The next table shows a comparison between the case studies with degradation and without:

	No degradation		**With degradation**	
	BEV consumption [MWh]	**BEV generation [MWh]**	**BEV consumption [MWh]**	**BEV generation [MWh]**
h01	32.909,6	264,5	53.437,1	0,0
h02	58.000,9	10,5	59.655,4	0,1
h03	90.682,1	9,7	99.036,5	0,0
h04	98.976,2	10,4	104.110,9	0,0
h05	79.221,7	9,6	65.818,8	0,2
h06	34.052,2	668,6	16.264,3	0,2
h07	12.362,6	4.486,5	3.011,9	0,2
h08	5.203,4	5.827,4	1.736,3	0,0
h09	4.596,0	9.078,6	1.233,6	208,8
h10	3.757,5	11.460,0	1.399,5	0,0
h11	5.287,7	7.348,0	2.445,0	0,0
h12	9.725,6	6.353,5	4.198,4	0,0
h13	10.713,2	2.924,1	4.380,0	0,0
h14	20.908,8	4,7	10.311,4	0,0
h15	30.453,2	4,0	17.910,5	0,0
h16	36.820,7	4,2	22.521,4	0,0
h17	34.184,7	5,2	18.489,5	0,0
h18	20.425,2	1.668,4	8.253,5	0,0
h19	8.060,8	8.316,4	626,8	0,0
h20	869,2	12.969,9	0,0	293,0
h21	0,0	17.520,9	0,0	1.980,9
h22	410,9	15.291,0	0,0	0,1
h23	2.377,8	3.301,2	81,6	585,7
h24	18.267,1	5.465,3	3.350,4	3.624,0

Table 20: Comparison between reference case studies with degradation and without.

The EV behavior for the case study without degradation has a much better correlation for consumption and generation with the evolution of prices and the distortion from the midnight restriction has not such a big effect compared to the generation from the rest of the hours, the same happens with the EV consumption.

The case study without degradation shows us that EVs would clearly tend to produce in the highest price hour even though if it's in the middle of the day and consume at the hours were prices are lower, this logic disappears as long as more distortions to this original modeling are included.

5. Emissions

Emissions in this case study reach the amount of 43,6 Mt CO_2.

6. Non-served energy

There is no non-served energy in this case study.

F. Summary

The next table shows some features that allow to compare the system benefits and effects of the different tariff and pricing schemes along with the cost of the energy consumed by EVs and the revenues from giving back energy to the grid.

	Reference with no tariff, LMP		**Ref w/o degradation and no tariff, LMP**		**Spanish tariff + single node**		**Efficient tariff + single node**		**Efficient tariff + LMP**	
	Cons	**Gen**	**Cons**	**Gen**	**Cons**	**Gen**	**Cons**	**Gen**	**Cons**	**Gen**
EV costs and revenues [€]	18.504.690	370.880	21.944.682	7.293.057	16.286.320	129.972	15.991.733	1.293.707	21.713.918	4.200.711
Costs-Revenues [€]	18.133.810		14.651.625		16.156.348		14.698.025		17.513.208	
Losses [MWh]	14.770.007		14.912.405		14.621.709		15.037.616		14.978.427	
Thermal costs [M€]	4.326		4.323		4.357		4.354		4.351	
Demand [MWh]	286.726.460		286.825.040		285.464.454		286.238.446		286.794.953	

Table 21: Main features for comparison between the different simulations.

. In Table 22, the behavior of EVs in the different simulations is shown.

MWh	Reference with no tariff, LMP		Ref w/o degradation and no tariff, LMP		Spanish tariff + single node		Efficient tariff + single node		Efficient tariff + LMP	
	Cons	Gen	Cons	Gen	Cons	Gen	Cons	Gen	Cons	Gen
h01	53.437	0	32.910	264	90.755	1.618	72.246	0	80.815	520
h02	59.655	0	58.001	10	98.554	0	53.432	0	59.112	0
h03	99.036	0	90.682	10	69.697	0	61.195	0	90.110	0
h04	104.111	0	98.976	10	80.001	0	51.240	0	95.795	0
h05	65.819	0	79.222	10	70.811	0	46.404	0	76.587	0
h06	16.264	0	34.052	669	13.354	598	24.789	0	36.483	277
h07	3.012	0	12.363	4.487	0	229	4.949	0	9.097	196
h08	1.736	0	5.203	5.827	0	0	4.079	0	2.587	17
h09	1.234	209	4.596	9.079	0	0	2.160	0	2.135	1.006
h10	1.399	0	3.758	11.460	0	0	1.621	0	1.446	2.330
h11	2.445	0	5.288	7.348	76	870	8.086	0	2.709	415
h12	4.198	0	9.726	6.353	516	0	10.462	0	3.808	322
h13	4.380	0	10.713	2.924	0	0	15.554	0	6.084	170
h14	10.311	0	20.909	5	0	0	31.476	0	12.742	0
h15	17.910	0	30.453	4	0	0	40.235	0	23.126	0
h16	22.521	0	36.821	4	0	0	43.187	0	27.574	0
h17	18.490	0	34.185	5	0	0	26.173	0	21.584	63
h18	8.254	0	20.425	1.668	0	0	13.068	0	10.951	537
h19	627	0	8.061	8.316	0	0	3.967	0	2.337	482
h20	0	293	869	12.970	0	276	295	0	313	10.475
h21	0	1.981	0	17.521	0	0	230	462	504	12.163
h22	0	0	411	15.291	4	0	298	34	18	10.125
h23	82	586	2.378	3.301	2.550	422	2.605	0	3.520	1.516
h24	3.350	3.624	18.267	5.465	21.033	392	8.780	31.700	6.380	36.061

Table 22: EV behavior comparison between all the simulations.

VI. Conclusions

In this section the main findings of the thesis are summarized, but in order to give some structure to these findings some relevant questions are to be answered. These questions should try to clearly approach the main conclusions extracted from the thesis, like: how does taking into account the degradation of batteries affect the behavior of electric vehicles, if tariffs really affect the behavior of EVs and how is this affected and if the system is really benefitted from the introduction of EVs and its efficient operation.

A. How does battery degradation affect EV behavior?

From the different simulations, it can be seen that adding the degradation effect to the ROM model makes the EVs take into account the opportunity cost of not only delivering the energy consumed at a certain hour and not delivering it at another but the opportunity cost of the capacity reduction that the battery suffers each time it is used.

Marginal prices increase and energy injected from EVs reduces substantially when including the degradation effect on the model. When thinking in delivering energy back to the grid, agents should not only take into account the cost of consuming energy to store it and the efficiency in the process, but also the cost of replacing the capacity lost in the process due to the degradation of batteries when flows occur.

This increases the hourly price differences at which EV would obtain benefits for delivering energy back to the grid. Generation of EVs happen in most quantity in those case studies where the spread of prices is higher (i.e. Efficient Tariff with LMP) to compensate that capacity loss.

B. How do tariffs affect the behavior of EVs and what benefits can be extracted for the system?

The volumetric charge of the network cost in the Spanish access tariff increases the prices that EVs see, decreasing their interest in consuming energy to later on deliver it back if prices are high enough. Even though it is true that EVs with the Spanish tariff charge during the night and deliver the energy in the highest price hours, the energy charge that is applied to recover network costs distorts the price signals that agents see. This is proved in the efficient tariff case studies, EVs generate back to the grid much more energy than with the Spanish tariff because the network costs are recovered through two charges, capacity, and fixed charges, but none of them energy based.

By penalizing those hours in which the demand is higher and letting the rest of hours with only energy hourly marginal prices, the demand from EV increases because EVs are willing to store the energy from the system and to deliver it back when prices are high enough and they are compensated for the battery capacity and efficiency losses. This is one of the benefits that the system can extract from the penetration of EVs: an added capacity storage

An extra benefit can be extracted from this storage capacity that EVs deliver to the system: less price variability for the end user. Due to new storage capacity from EVs prices reduce their spread due to the operation of EV’s stored energy → Consuming energy in low price hours to later on deliver it back in higher price hours → Increasing the price in lower price hours and lowering the price in higher price hours.

From Table 21 some interesting ideas can be described. The simulation that has a tariff implemented and shows the lowest cost is the one in which the efficient tariff is implemented along with a nodal pricing scheme, even though the losses are not the lowest and neither is the demand. It is the simulation with a tariff modelled in which the generation from EVs is highest, what proves the idea commented along this thesis that the efficient tariff promotes the flexibility of the EVs.

At first it could be thought that when increasing the demand losses would increase, but if the columns from Table 21 with the efficient tariff and LMP and the reference case with no degradation are observed and compared to the others, it is sought that even though demand from EV increases, losses do not increase in a proportional manner.

VII. Future work

In this thesis, the entire study is done considering that EVs are the resources in the aggregators node, but as it has been mentioned several times during the thesis other distributed energy sources can be modelled with the ROM.

Therefore, future work can be carried out adding other distributed resources like batteries, solar PV generation or local demand. In this thesis, the study has focused on analyzing the impact of aggregating EVs on the system, but also PV generation could be added. In this way, the impact of having available storage together with solar PV generation could be analyzed.

Another future line of research is simulating an aggregator node with demand, EVs, batteries and solar generation. This could be done in order to address the impacts of more distributed systems in a scenario where battery storage becomes more economically attractive.

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Annex I

	Range [km]	Energy at Midnight [kWh]	Percent of use00 [%]																							
	Distance	**IniLoad**	**h01**	**h02**	**h03**	**h04**	**h05**	**h06**	**h07**	**h08**	**h09**	**h10**	**h11**	**h12**	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**
use001	60	4	0,0%	0,0%	2,0%	2,0%	4,1%	5,4%	5,7%	3,7%	3,0%	3,0%	3,2%	3,3%	3,7%	4,3%	4,6%	4,6%	6,5%	6,9%	9,9%	7,3%	5,9%	4,4%	3,5%	3,1%
use002	52	8	0,7%	1,3%	2,1%	3,0%	3,3%	5,7%	5,1%	5,0%	4,1%	6,1%	6,1%	6,8%	6,6%	5,8%	6,4%	6,2%	5,8%	4,7%	4,2%	3,5%	3%	2%	1%	1%

Table 23: Percent of range used of EVs every hour.

	Range [km]	Energy at Midnight [kWh]	Percent of plugged-in [%]																							
	Distance	**IniLoad**	**p01**	**p02**	**p03**	**p04**	**p05**	**p06**	**p07**	**p08**	**p09**	**p10**	**p11**	**p12**	**p13**	**p14**	**p15**	**p16**	**p17**	**p18**	**p19**	**p20**	**p21**	**p22**	**p23**	**p24**
use001	60	4	96,3%	96,5%	95,7%	91,8%	84,2%	73,2%	62,8%	56,0%	53,0%	50,7%	48,2%	47,2%	46,4%	46,4%	47,6%	49,1%	52,6%	57,0%	61,9%	68,5%	73,3%	78,1%	84,1%	87,5%
use002	52	8	95,2%	93,7%	89,7%	84,9%	78,8%	71,8%	66,2%	61,7%	61,4%	61,7%	61,7%	61,6%	62,7%	64,8%	67,9%	70,9%	74,6%	77,7%	81,1%	85,3%	88,6%	91,3%	93,3%	93,2%

Table 24: Percent of EVs plugged to the grid at every hour.