Second life batteries of electric vehicles: analysis of use and management models

Héctor Rallo Tolós

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Second Life Batteries of Electric Vehicles: Analysis of Use and Management Models

Author: Héctor Rallo Tolós
Thesis Advisor: Dra. Beatriz Amante García

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Abstract

The mobility of the future undoubtedly involves the electrification of vehicles. The increase in social awareness towards a reduction in CO_2 emissions, together with the introduction of new laws regulating them, has finally led to an increase in the sales of electric vehicles. Furthermore, this trend is expected to continue to increase due to the global interest in reducing these emissions.

The growth in sales has meant that lithium-ion batteries have become an indispensable element in the automotive sector. The overall emissions of an electric car are between 20 and 40% lower than those of conventional vehicles, with the current energy mix. With the increase in green power generation, the EU expects to reduce emissions by up to 75% by 2050 compared to fossil fuel vehicles.

The battery, like any other vehicle component, wears out over time and use. Car manufacturers recommend that when these batteries reach 70% of their health, they should be replaced, as the manufacturers cannot guarantee their proper functioning and they could suffer a drastic drop in capacity, i.e. in the vehicle's range.

However, before these batteries are recycled, there is a possibility that they could be reused, as they still have enough power and capacity, to be used in other, less demanding applications. As a result, the reuse of these batteries, whose cost represents between 30 and 40% of the final price of an electric vehicle, is seen within the automotive sector as a great possibility to reduce the selling price of the electric car and make it more competitive than internal combustion cars.

Batteries have therefore become an indispensable element not only for the automotive industry, but also for any application that needs to store electrical energy. Consequently, it is already suggested that there is a market niche where these batteries could have great potential. The objective of reducing the heavy dependence on fossil fuels has led to an increase in renewable energies in the European energy mix. Their intermittence opens the door for energy storage sources to cover the moments when there is no generation.

Giving a second life to electric vehicle batteries has prompted the research interest of this doctoral thesis, which analyses different new models of use and business once they are no longer valid for automotive.

Resumen

La movilidad del futuro pasa sin lugar a dudas por la electrificación de sus vehículos. El incremento de la conciencia social hacia una reducción de las emisiones de CO_2 junto con la introducción de nuevas leyes que las regula, ha provocado finalmente un incremento en la venta de vehículos eléctricos. Además, se prevé que esta tendencia siga aumentando debido al interés global en reducir dichas emisiones.

El crecimiento de ventas, ha propiciado que las baterías de Litio-Ion se hayan convertido en un elemento indispensable dentro del sector de la automoción. Las emisiones globales de un coche eléctrico son entre un 20% y un 40% menores que las de los vehículos convencionales, con el actual mix energético. Con el aumento de generación de energía verde, la UE prevé para 2050, una reducción de emisiones de hasta los 75% respecto a las generadas por vehículos propulsados por combustibles fósiles.

La batería, al igual que cualquier otro componente del vehículo, se desgasta con el paso del tiempo y el uso. Los fabricantes de automóviles recomiendan que cuando estas baterías llegan entre el 70% de su estado de salud, deberían ser sustituidas, ya que los fabricantes no pueden garantizar su buen funcionamiento y podrían sufrir una caída drástica de capacidad, es decir, en la autonomía el vehículo.

Sin embargo, antes de reciclar estas baterías, existe la posibilidad de que sean reutilizadas, ya que aún disponen de suficiente potencia y capacidad, para funcionar en otras aplicaciones menos exigentes. Como consecuencia, la reutilización de estas baterías, cuyo coste representa entre el 30 y el 40% del precio final de un vehículo eléctrico, se ve dentro del sector de la automoción, como una gran posibilidad para reducir el precio de venta del coche eléctrico y hacerlo más competitivo frente a los coches de combustión interna.

Las baterías se han convertido pues, en un elemento indispensable no sólo para la industria del automóvil, sino también para cualquier aplicación que necesite almacenar energía eléctrica. En consecuencia, ya se apunta de la existencia de un nicho de mercado donde estas baterías podrían tener un gran potencial. El objetivo de reducir la fuerte dependencia de los combustibles fósiles ha provocado un aumento de las energías renovables en el mix energético europeo. Su intermitencia, abre la puerta a fuentes de almacenamiento de energía para cubrir los momentos en que no hay generación.

Dar una segunda vida a las baterías de vehículo eléctrico, ha despertado el interés de investigación de esta tesis doctoral, la cual analiza diferentes nuevos modelos de uso y de negocio una vez éstas ya no son válidas para la automoción.

Resum

La mobilitat del futur passa sense cap mena de dubte per l'electrificació dels seus vehicles. L'increment de la consciència social cap a una reducció de les emissions de CO_2 juntament amb la introducció de noves lleis que les regula, ha provocat finalment un increment en la venda de vehicles elèctrics. A més a més, es preveu que aquesta tendència segueixi augmentant a causa de l'interès global en reduir aquestes emissions.

El creixement de vendes, ha propiciat que les bateries de Liti-Ió s'hagin convertit en un element indispensable dintre del sector de l'automoció. Les emissions globals d'un cotxe elèctric són entre un 20% i un 40% menors que les dels vehicles convencionals, amb l'actual mix energètic. Amb l'augment de generació d'energia verda, la UE preveu per al 2050, una reducció d'emissions de fins als 75% respecte les generades per vehicles propulsats per combustibles fòssils.

La bateria, a l'igual que qualsevol altre component del vehicle, es desgasta amb el pas del temps i l'ús. Els fabricants d'automòbils recomanen que quan aquestes bateries arriben entre al 70% del seu estat de salut, s'haurien de substituir, ja que els fabricants no poden garantir el seu bon funcionament i podrien patir una caiguda dràstica de capacitat, és a dir, d'autonomia el vehicle.

Tot i això, abans de reciclar aquestes bateries, existeix la possibilitat que siguin reutilitzades, ja que encara disposen de suficient potència i capacitat, per funcionar en d'altres aplicacions menys exigents. Com a conseqüència, la reutilització d'aquestes bateries, que el seu cost representa entre el 30 i el 40% de el preu final d'un vehicle elèctric, es veu dintre del sector de l'automoció, com una gran possibilitat per reduir el preu de venta del cotxe elèctric i fer-lo més competitiu enfront dels cotxes de combustió interna.

Les bateries s'han convertit doncs, amb un element indispensable no només per a la indústria de l'automòbil, sinó també per a qualsevol aplicació que necessiti emmagatzemar energia elèctrica. En conseqüència, ja s'apunta l'existència d'un nínxol de mercat on aquestes bateries podrien tenir un gran potencial. L'objectiu de reduir la forta dependència dels combustibles fòssils ha provocat un augment de les energies renovables en el mix energètic europeu. La seva intermitència, obre la porta a fonts d'emmagatzematge d'energia per cobrir els moments en que no hi ha generació.

Donar una segona vida a les bateries de vehicle elèctric, ha despertat l'interès d'investigació d'aquesta tesis doctoral, la qual analitza diferents nous models d'us i de negoci un cop aquestes ja no són valides per a l'automoció.

Agraïments

Aprofito aquest espai per expressar en primer lloc, el meu agraïment i reconeixement a la Dra. Beatriz Amante, directora del meu doctorat, pel seu inestimable suport, motivació i experiència científica al llarg d'aquest viatge. Sobretot, per estar constantment reptant-me a seguir millorant. Vull agrair molt sincerament als meus companys de la Universitat Politècnica, els moments compartits i les converses de valor incalculable, i per permetre'm aprendre al seu costat. Gràcies a la Gabriela, al Robert, al David... per contribuir de la manera que ho heu fet en les publicacions d'aquesta tesis. I un agraïment especial per al Dr. Lluc Canals pel seu gran coneixement del tema i per la seva exigència que m'han empès sempre cap a reptes més ambiciosos.

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No vull oblidar-me tampoc ni de l'Adrian ni de Steph. Un per haver passat pel mateix uns anys abans i aconsellar-me quan ho he necessitat. I l'altra, per ajudar-me a la feina tant feixuga de corregir el redactat de la tesis. I tampoc de tota aquella gent que d'una manera o una altra, de vegades fins i tot sense saber-ho, ha contribuït en aquest projecte.

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Gràcies a tots per ajudar-me durant tota la meva investigació doctoral i contribuir a fer d'aquesta una experiència única i inoblidable.

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Glossary

B2LC	Battery 2nd life cost
BEV	Battery Electric Vehicle
BJB	Battery Junction Box
BMS	Battery Management System
CMC	Cell Module Controller
CNT	Carbon Nanotube
DOD	Depth of Discharge
EU	European Union
ECN	Electrical Circuit Equivalent
EIS	Electrochemical Impedance Spectroscopy
EMS	Energy Management System
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric Vehicle
EVI	Electric Vehicles Initiative
FDP	Fossil Depletion Potential
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HTP	Human Toxicity Potential
HV	High Voltage
IC	Inverter Cost
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
LC	Labour Cost
LCA	Life Cycle Assessment
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
Li-S	Lithium-Sulphur
LLI	Loss of Lithium Inventory
LMO	Lithium Manganese Oxid
LTO	Lithium Titanate
MC	Material Cost
MDP	Materials Depletion Potential
MPPT	Maximum Power Point Tracking
NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LV	Low Voltage

OEM	Original Equipment Manufacturer
OCV	Open Circuit Voltage
PHEV	Plug and Hybrid Electric Vehicle
PV	Photovoltaics
ROI	Return of Investment
SEI	Solid Electrolyte Interphase
SESS	Stationary Energy Storage System
SME	Small and Medium Enterprise
SOC	State of Charge
SOH	State of Health
PTC	Positive Temperature Coeficient
UPC	Universitat Politècnica de Catalunya – BarcelonaTech
UPS	Uninterruptable Power Supply
WDS	Water-dispersed Sulphur
WHO	World Health Organization

Chapter 1

Organization of the thesis

Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.

Albert Einstein.

This thesis was born as a consequence of the joint interest between **SEAT S.A.** and the **Universitat Politècnica de Catalunya – BarcelonaTech (UPC)** to continue investigating together the business around electro-mobility. This is a great opportunity for the university to work close to the industrial ecosystem, and at the same time, it is also a great opportunity for the industry, since they can see the scientific advances first hand and can generate a competitive advantage over other competitors. In fact, some of the information outlined in the following chapters comes from the work done together with SEAT and UPC in the framework of this thesis.

This thesis is organized into 12 chapters and attempts to take both, academia and practitioners' point of view into account. With this purpose, it is structured in three main blocks.

The objective of the **first block** is to explain from an academic point of view the structure of the document, contextualise the reader within the framework of the research and determine the objectives of this thesis together with the methodology used throughout chapters one to five.

The thesis starts with the **Chapter 1** where the structure and the chapters are explained in detail. Immediately, **Chapter 2** continues with the introduction. This chapter introduces the reader to electro-mobility sector with a brief summary of the Electric Vehicle (EV) and how society is pushing its massive entry into the market highlighting the points where improvement is needed if sales of Internal Combustion Engine Vehicles (ICEVs) are to be surpassed. Then, the variants of the most commonly used batteries in EVs are described according to their chemical composition. To conclude the introduction, the possibility of reusing these batteries when they reach the end of their automotive life in static energy storage applications before being recycled is introduced.

Chapter 3 presents the State of the Art of the Stationary Energy Storage Systems (SESSs) and their possible applications. Next, the chapter focuses on Li-ion batteries, and specifically on projects carried out with second life batteries coming from EVs together with an extended overview of many investigations validating those 2nd life batteries in several applications from the economic and technical point of view paying special attention to the ageing of the batteries and their disassembly from the car to a functional unit for proper reuse.

Once detailed up to what point science has investigated battery reuse and battery's 2nd life, **Chapter 4** establishes the main objectives of the thesis and **Chapter 5** explains in detail how these objectives will be carried out.

The **second block** outlines the most experimental part of the thesis focusing on all stages necessary to determine the economic viability of the reuse of electric car batteries.

Chapter 6 analyses the entire process of dismantling the battery from a point of view of human and material resources that has an impact on time and cost. Firstly, the removal of the battery from the vehicle. Then, the battery is examined and dismantled at module or cell level depending on the assessment results and the use it will be given in its second life.

This chapter is based on the article entitled: *Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries* published in the journal *Resources, Conservation and Recycling* with an Impact Factor of 8,086.

Giving continuity to the previous, **Chapter 7** evaluates in detail the economic feasibility of locating a battery treatment centre in Spain considering the prognosis of car sales in Spain.

Once the battery is ready for a second life, the next step is to analyse in which applications the installation of these batteries is viable in terms of ageing and economics. For that reason, **Chapter 8**, expands on a battery ageing model developed previously by the UPC including a sophisticated economic model that can determine both the technical and economic feasibility of reusing EV batteries in any static energy storage application.

Chapter 9, using two real case studies, is responsible for validating the model implemented in the previous chapter.

This chapter is based on the article entitled: *Lithium-ion battery 2nd life used as a stationary energy storage system : Ageing and economic analysis in two real cases* published in the *Journal of Cleaner Production* with an Impact Factor of 7,246.

Chapter 10 brings together all of the above, to implement a second life battery project in a domestic case together with photovoltaic energy in order to reduce the cost of the electricity bill.

And to conclude block two, **Chapter 11** introduces another chemical variant for EV, Lithium-Sulphur. A comparison is made with current Lithium-ion batteries, from a chemical and physical characteristics point of view, paying particular attention to battery modelling. An environmental and cost analysis are also performed.

This chapter is based on the article entitled: *Comparison of the state of Lithium-Sulphur and lithium-ion batteries applied to electro-mobility* published in the *Journal of Environmental Management* with an Impact Factor of 5,647.

Finally, in the **third block**, **Chapter 12** sets out the conclusions that have been drawn from this thesis and opens the discussion on the new lines of research that are opening up.

Chapter 2

Introduction

The time you enjoy wasting is not wasted time.

Bertrand Russell.

2.1 The electric car

When we think of an electric car, the first thing that comes to mind is something very new which could even possibly be the best alternative to Internal Combustion Engine Vehicles (ICEVs), but nothing could be further from the truth, the history of the electric vehicle began in the mid-19th century. However, the high cost, low top speed, and short range of the Electric Vehicles (EVs), compared to ICEVs, at that time, led to a worldwide decline in their use. Nevertheless, it was not until the end of the 20th century that the world's population became aware of the side effects of ICEVs and began to be concerned about their environmental impact.

As reported by the World Health Organization (WHO) every year three million deaths are linked to outdoor air pollution. This figure is relevant above all when considering that 92% of the world's population lives in places where the air pollutants exceed the WHO limits [1].

The European Parliament wants to counteract this phenomenon by introducing a new regulation which requires that all vehicles manufactured after 2020 emit less than 95 g/km of CO_2 and, for those manufactured from 2025 onwards, the maximum emission should be of 68–78 g/km [2]. In order to meet these requirements, the European vehicles manufacturing industry is focusing its efforts to develop new vehicle models with lower pollutant emissions, and accordingly, they are working on the electrical vehicles technology. In the whole life cycle, Greenhouse Gas (GHG) emissions in Europe of an EV are around 10–20% less than an ICEV [3]. Furthermore, it must be considered that only the transportation sector produces around 23% of the global CO_2 emissions connected to energy [4].

For instance, the Electric Vehicles Initiative (EVI), which is an organisation that represents multiple countries, focuses its activities on supporting the penetration of the EV in the market to achieve at least, the 20 million units of EV sold. According to International Energy Agency (IEA), the electric vehicles stock for the countries associated with this organisation, in 2015 was 1,26 million. This value is 100 times larger than the figure estimated in 2010 by 2015 and it exceeds the barrier of 1 million of EVs sold [5]. By 2020, the new target set by EVI is achieving 20 million EVs on the road, which would represent a share of 1,7% by 2020 [6] and 30% by 2030 [7] of the total vehicles in the world. These shares are predicted to increase worldwide in the coming years from the current 1.2 billion to around 2 billion by 2040 [8]. Updated statistics show that in 2018, the EV fleet was more than 5.1 million units that means up 2 million from 2017. China was the country with the world's largest EV fleet, just before Europe (mainly Norway) and the United States [7].

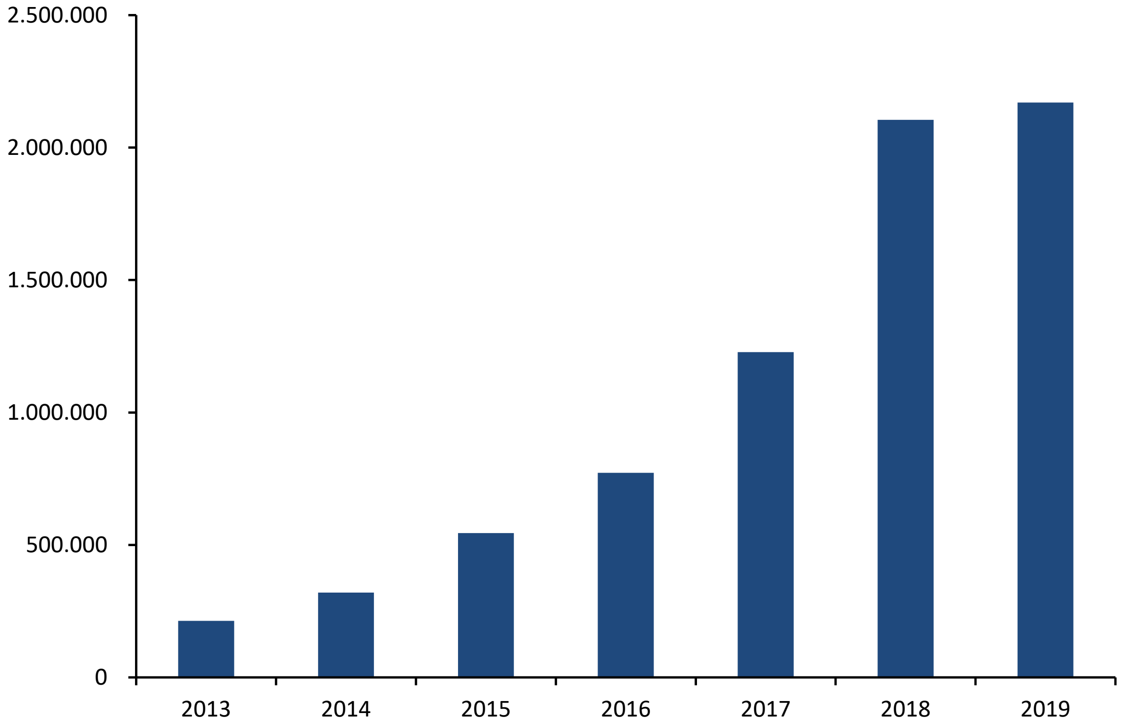
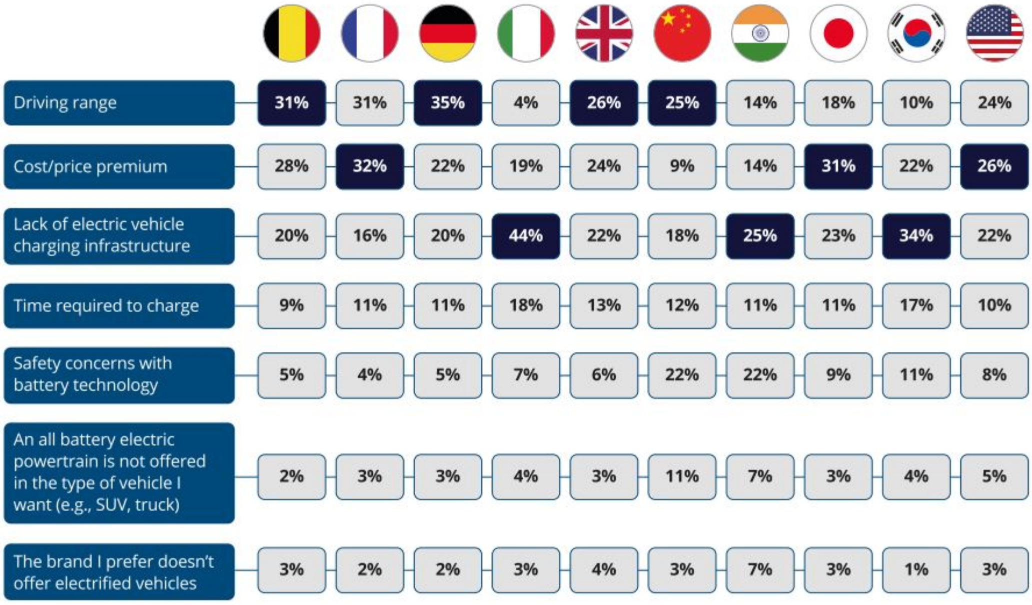


Figure 2.1: PHEV + EV sales worldwide [9]

A few years ago, car buyers were still quite reticent to purchase an EV [10], but recently, this behaviour has changed as shown in Figure 2.1. This trend is expected to continue growing due to the global interest in reducing CO_2 emissions, along with new policies in large European cities restricting the most polluting cars driving in the city. Although EVs can meet the everyday needs of most users, they are still far from the performance offered by ICEVs. The major concern of potential EV users, as shown the Figure 2.2, is related to issues regarding the availability of EV charging stations, the driving range and the final cost of the vehicle. In countries such as Belgium, Germany, United Kingdom and China their main concern regarding the electric car is the driving range with 31%, 35%, 26% and 25% respectively. In contrast, in France, Japan and USA their doubt is with the cost of the EV with 32%, 31% and 26% respectively. Lastly, in Italy, India, South Korea the lack of charging infrastructure is presented as the greatest difficulty in buying an EV with 44%, 25% and 34% respectively. So, actually the concerns of those countries are not in contrast, but they are very similar and they put nearly an equal weight on them. Other factors such as the time required to charge and the battery safety, seem not to be a cause for concern to potential buyers.



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Driving range	31%	31%	35%	4%	26%	25%	14%	18%	10%	24%
Cost/price premium	28%	32%	22%	19%	24%	9%	14%	31%	22%	26%
Lack of electric vehicle charging infrastructure	20%	16%	20%	44%	22%	18%	25%	23%	34%	22%
Time required to charge	9%	11%	11%	18%	13%	12%	11%	11%	17%	10%
Safety concerns with battery technology	5%	4%	5%	7%	6%	22%	22%	9%	11%	8%
An all battery electric powertrain is not offered in the type of vehicle I want (e.g., SUV, truck)	2%	3%	3%	4%	3%	11%	7%	3%	4%	5%
The brand I prefer doesn't offer electrified vehicles	3%	2%	2%	3%	4%	3%	7%	3%	1%	3%

Figure 2.2: Customer concerns regarding battery electric vehicles [11]

The cost of the EV is still higher than the cost of ICEVs despite the cost of Li-ion battery having decreased [12] and probably being the main obstacle that EVs have to overcome if they want to win the battle for the ICEV, where the cost allocated to the production of the battery fabrication constitutes from 30 to 40% of the total EV price [13]. Therefore, the evolution of the electric car depends mainly on the evolution of battery capacity and cost. Table 2.1 shows the best-selling electric car variants at this time.

Table 2.1: Types of electric vehicles

Type	**Description**
HEV	This type of vehicle includes at least two different types of energy sources for its own propulsion, and one of them must be electric. The other sources can be obtained from the combustion of gasoline, diesel, biofuel, etc. Hybrid Electric Vehicles (HEVs) usually include a generator to recharge the electric batteries using energy from another source when electric traction is not in use
PHEV	The Plug and Hybrid Electric Vehicles (PHEVs) are a specific type of hybrid electric vehicle, which not only recharge their electric battery using an internal generator, but can also recharge the battery by plugging in an external power source
BEV	The Battery Electric Vehicles (BEVs) only have one electrical source for their propulsion. This battery-powered electric motor must be charged by plugging in an external power source

2.2 Batteries

Li-ion batteries are energy storage systems based on the chemical reaction that occurs between electrodes (anode and cathode) with the lithium ions being the charge carrier [14]. Nowadays, it has been demonstrated that Li-ion batteries technology provides the most advanced systems to store and recharge energy [15]. In fact, Li-ion technology clearly dominates the market of energy storage systems for electro-mobility due to the high specific energy, long life cycle, low internal resistance, low self-discharge, short charging times among other things. The following are examples of Li-ion battery types and most prominent technologies used in the automotive market today [16][17]:

- Lithium Nickel Manganese Cobalt Oxide (NMC)
  One of the most successful and used Li-ion systems is the cathode combination of nickel-manganese-cobalt. The secret of NMC lies in combining nickel and manganese. An analogy of this is table salt in which the main ingredients, sodium and chloride, are toxic on their own but mixing them serves as seasoning salt and food preserver. Nickel is known for its high specific energy but poor stability; manganese has the benefit of forming a spinel structure to achieve low internal resistance but offers a low specific energy. Combining the metals enhances each other strengths.The vast majority of the manufacturers such as Volkswagen, Smart, Nissan and BMW among other utilize these li-ion batteries.

- Lithium Nickel Cobalt Aluminium Oxide (NCA)
  This battery type shares similarities with NMC by offering high specific energy, good specific power and a long life span although it has some disadvantages such as less safety and higher cost in comparison to other Li-ion battery types. Tesla is the most well known electric vehicle manufacturer that uses NCA batteries.

- Lithium Manganese Oxide (LMO)
  Li-ion cell with lithium manganese oxide as cathode material. The architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improved current handling. A further advantage of spinel is high thermal stability and enhanced safety, but the cycle and calendar life are limited.

- Lithium Titanate (LTO)
  LTO replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode can be lithium manganese oxide or NMC. Li-titanate has a nominal cell voltage of 2,40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristic, but the disadvantage of having a much lower energy density.

- Lithium Iron Phosphate (LFP)
  LFP batteries provide good energy density ratio, comply with safety requirements, and offer a good performance and thermal resistance. Efficient characteristics include power-to-weight ratios, high safety features and a good thermal resistance.

Each of these type of batteries, as Figure 2.3 shows, presents different characteristics regarding energy density, power, durability, thermal resistance and cost. NCA, LFP and NMC are the most widely used chemical variants in the automotive world. NCA distinguishes itself for being the best alternative in specific energy, specific power and lifetime but all this at the cost of dubious safety and high cost. On the other hand, LFP stand out for its high cost/lifetime ratio. Finally, NMC is possibly the most balanced variant in all aspects.

Li-ion batteries are made by connecting different Li-ion cells in different configurations (parallel, series or combination of both). A module consists of multiple battery cells and batteries are then composed by multiple modules (battery pack). The capacity of the batteries may vary from 10 kWh from for PHEVs to 50-100 kWh for BEVs. Thus, the number of cells contained in each battery varies depending on the chosen capacity.

The classic configuration of a Li-ion cell consists of a cathode (positive electrode) and anode (negative electrode) and an electrolyte composed of lithium ions. Each electrode is isolated from each other using a separator.

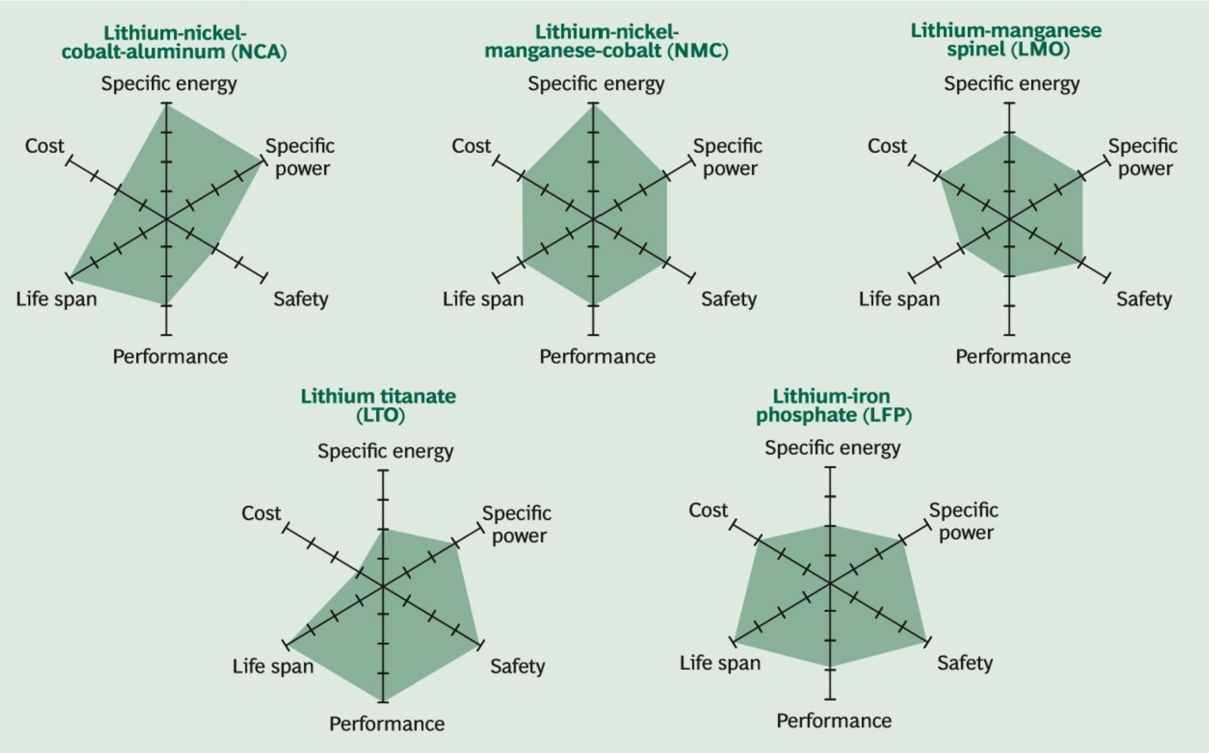


Figure 2.3: Battery chemistries comparison [18]

The cost of a Li-ion battery is accounted for considering their total capacity and is expressed in terms of €/kWh. Despite the current high costs of these batteries, it is expected that it can reach half of its cost by 2030 [19].

The use of Li-ion batteries is also adequate in several other applications apart from the vehicles, as they can be employed as Stationary Energy Storage System (SESS) and portable electronic devices with an increasing demand each year. In fact, it is estimated that the demand of Li-ion batteries will increase by 14% every year [20]. It is estimated that by 2030 the world demand for storage will be equal to 150 GW to be provided by batteries that will support the generation and consumption of electricity from renewable sources [21].

In detail, EV and SESS market forecasts are:

- EV Market trends: though the Chinese and US market dominate the sales of EV, it is expected that 20% of the total amount of EV that are produced will be sold in Europe. Moreover, it is estimated that 46.540 MWh capacity from EV Li-ion batteries will be available by 2030 while it might increase up to 215.200 MWh in 2040 [22].
- SESS Market trends: it has been recorded that up to December 2016, 1227 SESS projects utilized Li-on batteries where the installed power achieved 1930 MW. The annual growth of projects that employed SESS using Li-ion technology is around 55%.

Although the research to improve Li-ion batteries is very active, this technology is reaching its theoretical limit (200-250 Wh/kg) [23], which is not good enough to meet the market requirements [24]. For this reason, both industries and research institutions are showing interest in the study of alternative electrochemical energy storage systems with higher energy density. At present, one of the most promising technologies is Lithium-Sulphur (Li-S) not only for its higher theoretical energy density (about 2600 Wh/kg) but also for the relatively inexpensive and non-poisonous materials used in its manufacture that are expected to reduce the overall battery price and environmental impact [25].

2.3 Recycling or 2nd life?

Batteries have become an indispensable element for the development of EVs, but those, like any other car component, wear out over time and use. When EV batteries lose between 20 and 30% of their initial capacity, it is considered that they are no longer adequate for traction [13]. When this happens, EV manufacturers suggest that the batteries should be replaced otherwise the EVs could have issues regarding the driving capability (for instance shorter driving ranges or a decrease in the power outputs) or even safety problems that may lead to inadequate braking capabilities or loss in the battery storage capacity. In general this loss of capacity occurs after 8 years or 160.000 km [26].

Even though EVs are more environment and climate-friendly than ICEVs [27], the disposal of EV batteries at the end of their automotive lifecycle has emerged as a serious environmental concern. Lithium-ion batteries used in EVs contain metals, rare earth elements and toxic materials that adversely affect the environment and present a risk to human health [28]. Therefore, scrap EV batteries should be recycled at specific facilities to recover valuable materials efficiently and safely. In addition, another factor to consider is that the Extended Producer Responsibility (EPR) requires all EV manufacturers to recycle all its components, including batteries. The recycling of these batteries must be carried out in accordance with the directive 2006/66/EC of the European Parliament [29].

The two main recycling processes are pyrometallurgy or smelting and hydrometallurgy, both being chemical separation processes that are often used together or in various combinations to recover most of the materials within the battery [30]. There are other processes, such as the mechanical approach to recover metals by extracting the electrolyte and breaking the cell apart [31] or the leaching and precipitation used to focus on Lithium and Cobalt [32], that might be used as recycling processes to maximize the recovery of elements. However, due to the still low quantity of EV batteries being recycled and the different existing types (different shapes, sizes, chemistries, etc...), it is difficult to automate processes and specialize in any type of battery. This causes the recycling processes to treat batteries like a general waste, only focusing on recovering the critical raw material. Consequently, these recycling approaches do not provide enough economic profit. For instance, 1 Kg of CO_2 is saved for each kilogram of recycled battery, but recycling Li-ion batteries is five times higher than extracting virgin material [33]. At the moment, only 5% of Li-ion batteries are recycled across Europe [34].

On the other hand, when the batteries are no longer valid for use in the vehicle due to capacity loss, it has been demonstrated in several projects that these batteries still have enough energy to be used for other less demanding second life purposes, such as in SESSs. The SUNBATT project carried out by SEAT is a good example of battery reuse [35]. In consequence they can be reused while delaying the final recycling phase by up to 20 years, leaving space for recycling to present positive revenues [36]. Moreover, the SESSs requirements are much lower than the ones of EVs, which corroborates that the loss of power and capacity of reused batteries is not a major problem for most stationary energy applications [37].

The effectiveness and success of the SESS are clearly determined by the economic evaluation of the projects and therefore, the market requires that the SESS systems provide reasonable capital cost and life- cycle cost. That implies that using a battery as energy storage technology can be efficient from an economic perspective as long as its cost is, at maximum, equal to the cost of electricity generated by conventional fossil-fuel based technology and available in the grid. Apart from that, SESS systems need to take into account that they should provide higher reliability, durability, and safety performance, together with a minimum shelf life (more than 15 years) and cycle life (e.g. up to 4000 deep cycles) [38].

Giving a second life to these batteries can be seen by car manufacturers as a two-fold opportunity: firstly, to open a new business line (either exploited by themselves or by third parties) where the benefits could directly impact the price of the battery, and therefore reduce the selling price of the EV. Secondly, to be capable of responding to the environmental issues related with

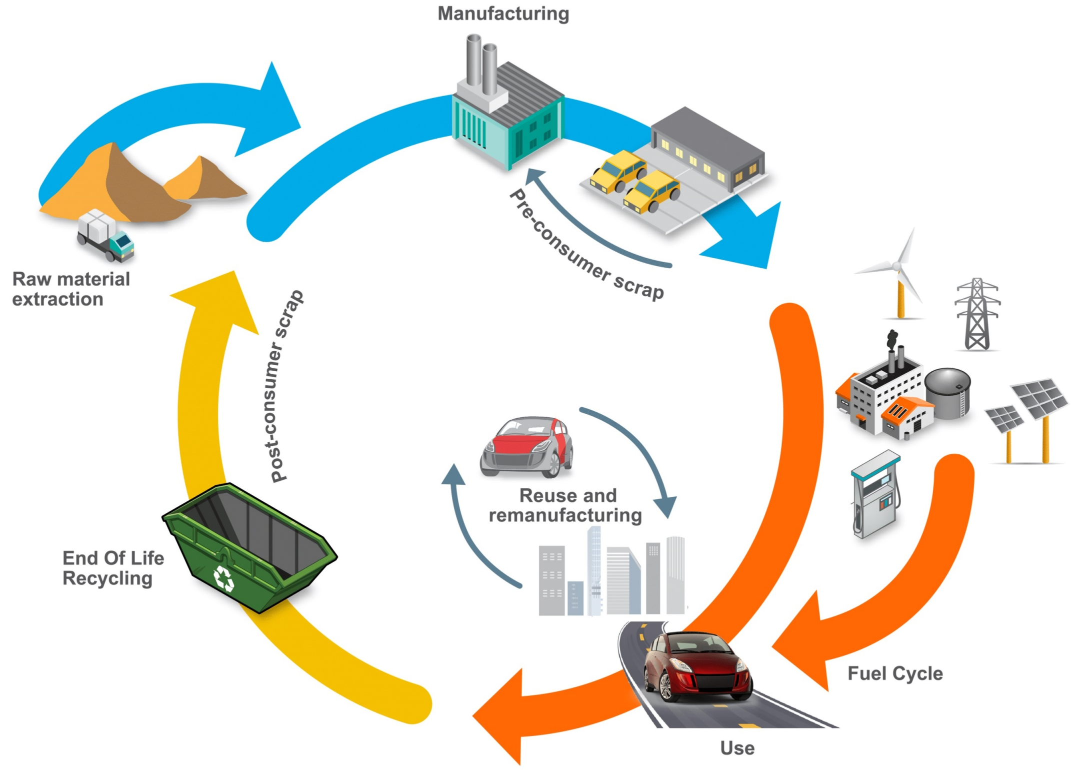


Figure 2.4: Vehicle life cycle

their use. However, between the first and second life of batteries there is a regulatory gap to cover that needs to be addressed.

From an environmental perspective, the Circular Economy Package from the European Commission clearly reports that the reparability, upgradability, durability, and recyclability of products is one of the major targets to implement a circular economy [39].

Figure 2.4 shows the complete life cycle of the vehicle, from the extraction of raw materials to the recycling process, going through the stages of vehicle manufacturing and use in their automotive life and the reuse as a SESS in a second life.

Depending on the State of Health (SOH), batteries could be re-used back into vehicles as replacements (when SOH is high enough), to second life, or directly for dismantling and recycling (when SOH is really low). Moreover, in cases of massive crash of an EV, it would certainly be very risky to re-use its battery and it could be appropriate to send it directly for recycling.

Chapter 3

State of the art

We live on an island surrounded by a sea of ignorance. As our island of knowledge grows, so does the shore of our ignorance.

John Archibald Wheeler.

The first step in all investigations consists of exploring what other researchers have achieved before in the fields related to the research topic. Therefore, this chapter presents the state of the art, which will allow us to look back and analyse what has done before in the fields of stationary energy storage systems and the possibility of doing business with them, the second life batteries and the recycling. These will allow us to understand the objectives of this thesis and will determine the different lines of work.

3.1 Energy storage systems

How we generate energy is one of the biggest challenges of our time. Climate change in the wake of the burning of fossil fuels to power our energy system and move our vehicles is threatening our planet and our lifestyle.

Electricity can be easily generated, transported and transformed. However, until now it has not been possible to store it in a practical, easy and cost-effective way. This implies that electricity must be generated at all times in accordance with demand and, consequently, renewable energies require the support of Stationary Energy Storage Systems (SESSs). Efficient energy storage is a fundamental pillar of energy transition: it makes renewable energy production more flexible and ensures its integration into the system.

Electrical energy cannot be stored as such and must be transformed into other types like mechanical or chemical energy. There are many different energy storage technologies available. Heat, water, chemical, kinetic, pressure, and some more are all capable of storing energy for later use (see Figure 3.1). Storage systems can bring value to each and every step of the electricity supply chain, with the final objective of maximising the integration of renewable energy and providing greater efficiency and safety to the entire electricity system. Depending on their capacity, energy storage systems are divided into: long, medium and short term. Thanks to its ability to take advantage of intermittent energy resources and variable energy demand, this technology has attracted regular investment during recent years [40]. A list of the energy storage key applications with a brief description is presented in Table 3.1

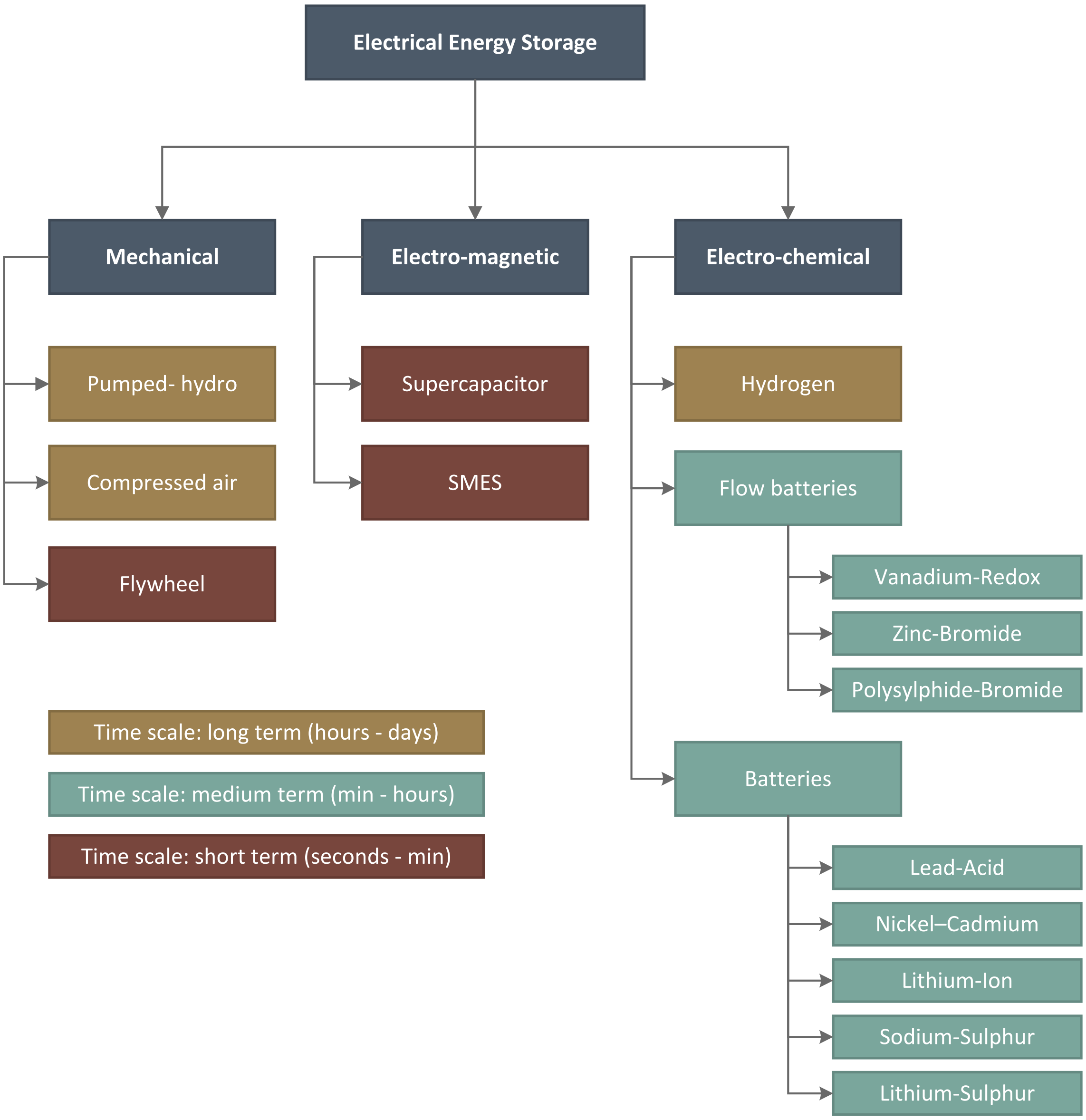


Figure 3.1: Energy Storage Technologies [41][42]

In recent years, the renewable energy sector has viewed lithium-ion batteries as the solution to its main problem: storage of the energy generated due to its low weight and high efficiency, only one obstacle has so far kept lithium batteries from becoming the main storage technology for renewable energy: its high cost. This situation, however, seems to be changing. As it can

Table 3.1: Services that SESSs can supply to the electricity grid [41][40]

Application	**Description**
Energy arbitrage	Separation of the instants of energy purchase and selling of energy in order to maximize the benefits
Peak shaving	Shifting electric energy demand from high price/demand periods (peaks) to low price/demand periods.
Seasonal storage	The ability to store energy for days, weeks, or months to compensate for a longer-term supply disruption or seasonal variability on the supply and demand sides of the energy system (e.g. storing heat in the summer to use in the winter via underground thermal energy storage systems).
Load following	Meeting hour-to-hour and daily load variations
Voltage support	Voltage support service is used to generate reactive power to offset reactance in the grid to maintain voltage within specified limits
Black start	A power source with the ability to go from shut down to operating conditions, without assistance from the grid after a blackout, and afterwards can energize parts of the grid
Power oscillation damping	The ability to change the output power in such a way to reduce the power oscillations in the low frequency range
Grid Inertial Response	The ability of an energy source, e.g. a generator to maintain its speed (frequency) when the load suddenly changes
Island operation mode	Batteries are useful to provide energy in island installations when the primary energy source is not available
Primary and secondary reserve	Automatic regulation service in charge with restoring the balance between production and consumption

be seen in the Figure 3.2, the cost of lithium-ion batteries will be significantly reduced in the coming years while its energy density increases.

Lithium-ion batteries have become one of the most important elements in the fight against climate change. They have the potential to change the automotive sector with the entry of the electric vehicle, while at the same time they can drive the total integration of renewable energies into the electric system. As Figure 3.3 shows, the increase in electric car sales will lead to a large availability of second life batteries which, due to its lower cost, will encourage the use of these batteries, after its first life in the vehicle, in a SESSs.

To date, the availability of second hand batteries is relatively low, but this has not prevented many projects from being carried out to demonstrate the technical feasibility of Electric Vehicle (EV) batteries integrated into a SESS. Like most, EV manufacturers want to take advantage of the possibility of giving these batteries a second life working as a SESS to open up new business, which could allow for a reduction in the final EV selling price, most of the demonstrative projects are led by an automotive company, usually at the hands of an electric company. Some examples are:

- The SUNBATT project led by SEAT and ENDESA was one of the first projects that demonstrated the good performance of the EV batteries working as a SESS in Spain. The SUNBATT container is connected to an 8 kWp solar carport, 3 EV chargers, 1 Fast EV charger and the grid, which is able to offer 90 kW peak power. All these elements

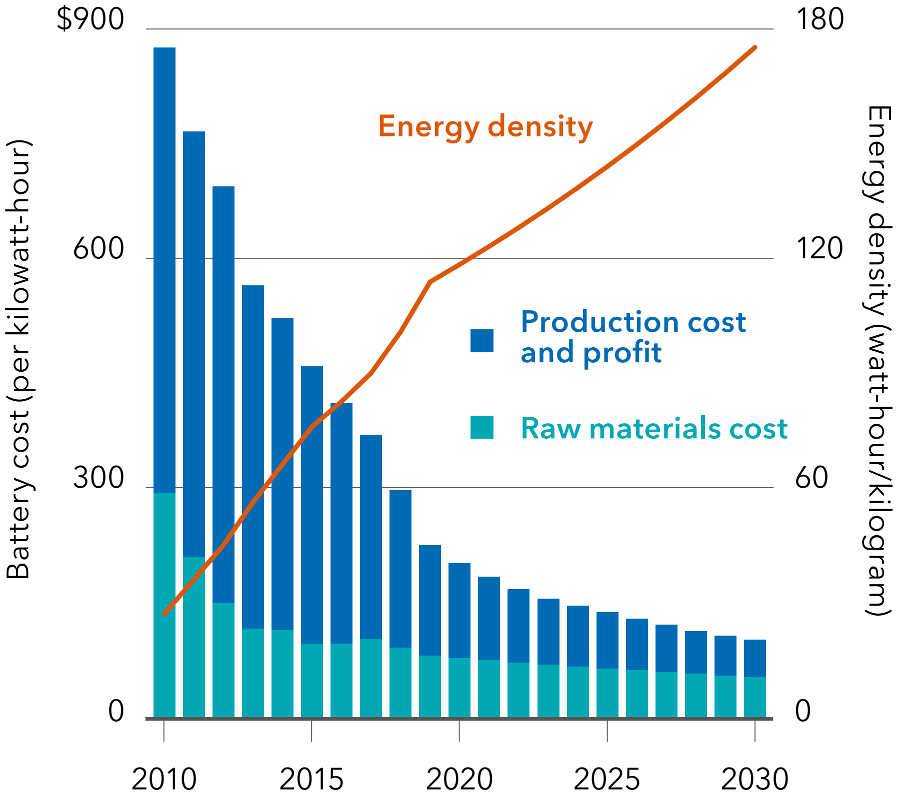


Figure 3.2: Cost and energy density of batteries, 2010-2030 [43]

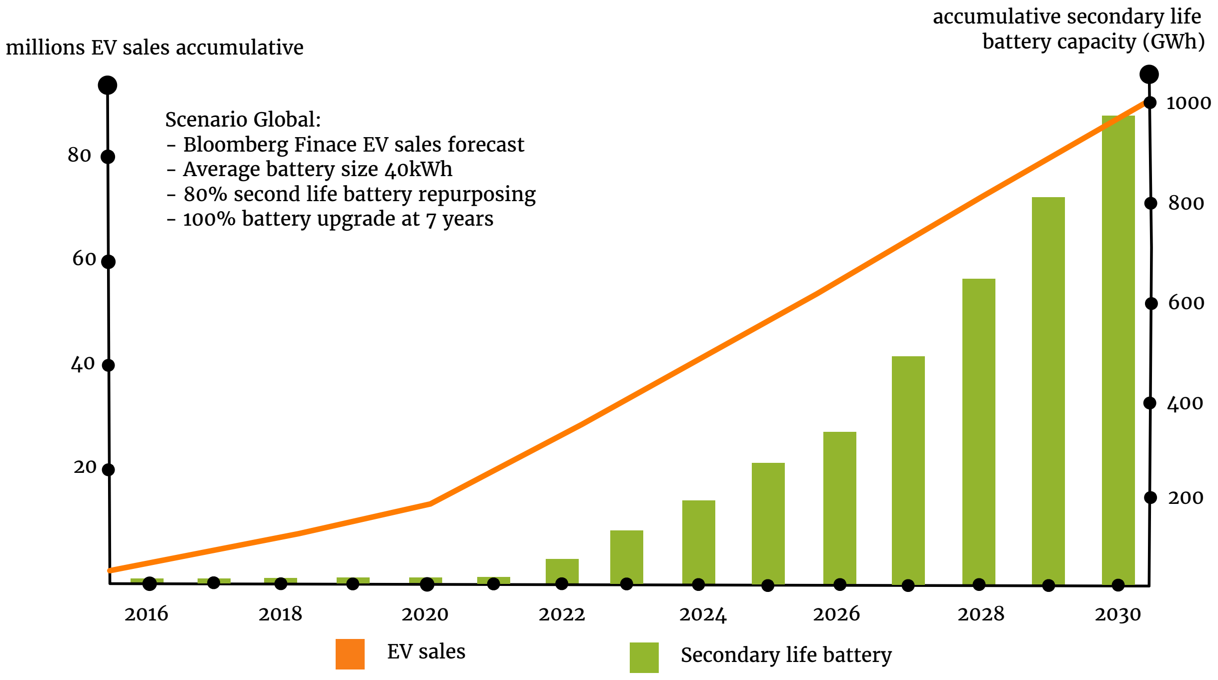


Figure 3.3: Global accumulative sales of EV and second life batteries [44]

interact with the SESS though an Energy Management System (EMS) offering a variety of possible applications and it allows testing the different real case stationary applications before releasing the product into the market [35].

From here, the connections and the direction of the energy flows offer many possibilities. The energy produced by the solar panels can be stored in the batteries and fed into the distribution network or consumed directly if a vehicle is connected to the charging point. The aim is to save on the electricity bill and achieve intelligent consumption.

This project served to technically validate the integration of the 2nd life batteries into the electrical network, by means of bi-directional converters and specific communication protocols. Figure 3.4 shows the SUNBATT project.

Figure 3.4: SUNBATT container located at technical centre of SEAT (Martorell - Barcelona)

- In 2019, AUDI put into operation the largest multi-use storage in Germany. The storage unit has a capacity of 1.9 MWh. The company utilized 20 used lithium-ion batteries for the project, all of which were sourced from Audi's test vehicles. The storage unit spans an area of roughly 110 square meters. The system has been designed to test various scenarios having different interactions between electric cars and the power grid [45].

  Audi claimed the 1.9 MWh storage system is big enough to provide charging services for roughly 200 electric vehicles. It also said that the installation is capable of supplying electricity for the entire 5.5-hectare EUREF Campus for slightly less than two hours. Figure 3.5 shows the reused batteries working as SESS on Berlin EUREF Campus.

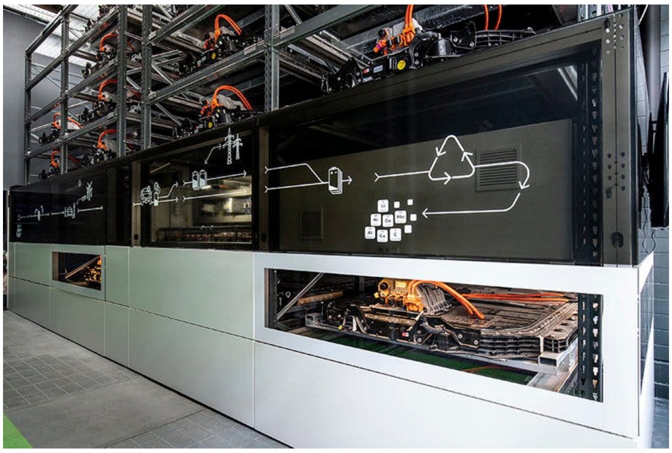


Figure 3.5: Audi Battery Storage Unit on Berlin EUREF Campus

- The SESS developed jointly by General Motors and ABB had five used Chevrolet Volt batteries repackaged as a modular unit capable of providing two hours of electricity needed by three to five average American homes. Specifically that means 50 kilowatt-hours of energy storage, and during a demonstration event the unit provided 25 kilowatts of power to run the support lighting and audiovisual equipment in an “off-grid” structure used for the demo event. The demonstration unit used ABB’s Energy Storage Inverter system and it’s claimed a similar system could be used to power a group of homes or small commercial buildings during a power outage or to gather electricity when it’s inexpensive (at night) and release it during the day when the electricity is more expensive [46]. Figure 3.6 shows the SESS developed by GM and ABB.

Figure 3.6: GM and ABB demonstrator in San Francisco (USA)

- Bosch, BMW and Swedish power company Vattenfall made a project to harness the potential of batteries used in EVs to provide stability to electrical grid infrastructure. 2MW/2MWh large-scale energy storage system was built using lithium-ion batteries from BMWs ActivE and i3 ranges of EVs. The onsite storage facility will be operated by Vattenfall for 10 years under the terms of the Second Life Batteries alliance. This project has determined that the usage of EV lithium-ion batteries in stationary applications offers the possibility of extending their life due to the batteries being able to work at shallower depths of discharge and less frequency cycles than in the EV. [47]. Figure 3.7 shows a scheme of the installation.

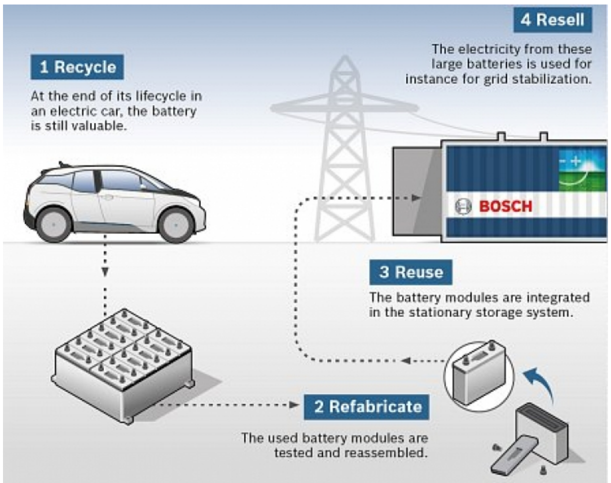


Figure 3.7: Second Life Batteries project schema to be build in Hamburg (Germany)

- Still in progress, the 3MW storage unit built from reused electric car batteries will be among the largest such projects in Europe. Located at the back of the Ajax Amsterdam arena it the result of collaboration between Nissan, Eaton and others. The 3 megawatt storage system will provide energy for the stadium, its visitors, neighbours and the Dutch energy grid. It will combine Eaton power conversion units and the equivalent of 148 Nissan LEAF batteries. The system guarantees the arena's energy supply even during a power outage. In turn, the energy storage balances supply and demand of energy in the Johan Cruijff ArenA and the grid. For example, the system will provide back-up power and provide relief to the energy grid by flattening the peaks that occur during concerts for example. The storage system with 3 megawatts and 2.8 – megawatts hour is enough to power several thousand households. This capacity also means that the energy produced by the 4,200 solar panels on the roof of the ArenA can be stored and used optimally[48]. Figure 3.8 shows the battery rack installed in the Amsterdam ArenA.

Figure 3.8: Second life LEAF batteries to power Amsterdam ArenA

- A total of 1920 second life battery modules are bundled in a plant in Elverlingsen in South Westphalia. With installed power output of around 9 MW and energy capacity of 9.8 MWh, the battery storage plant is available to the energy market, for example for supplying primary balancing power. Its modular design enables the system to continuously and fully automatically stabilize the power grid with balancing power [49]. Figure 3.9 shows the storage plant in Elverlingsen.

Figure 3.9: Second Life Batteries project in Elverlingsen in Germany

- Collaboration between Connected Energy and Groupe Renault on second-life battery energy storage technology. The batteries in the E-STOR were formerly used to power Renault Kangoo Z.E. vehicles in France. They have a combined energy storage capacity of 720 kilowatt hour and can deliver 1.2 megawatt in power. The batteries will provide firm frequency response to the grid, acting as a revenue generator. Maintaining stability of the network at its operating frequency of 50Hz is vital for enabling the addition of more distributed energy resources [50]. Figure 3.10 the battery connections inside the SESS.

Figure 3.10: Renault Second Life Batteries project in Belgium

3.2 Second life studies

Apart from all the pilot projects outlined, there are many open investigations in demonstrating the technical feasibility of electric car batteries working as energy storage during their second life. Instead, as far as the economic aspect is concerned, the opinion of the different authors differ as to whether or not the use of these batteries as a SESS is feasible.

Shi Jie Tong et al. examine through a prototype the feasibility of using second life batteries with energy from solar panels for the recharge of electric vehicles. The study determines that second-life batteries have a lower capacity and higher internal resistance than new batteries, but suggests that a good combination of reused cells can achieve better economic viability than current new lead-acid and Li-ion batteries with almost the same performance [51]. *C. Koch-Ciobotaru et. al.* also propose the integration of second life batteries in applications where renewable energy sources are used, where as in other cases, the technical feasibility of all these types of projects is demonstrated. An economic return is also demonstrated since the integration of the batteries in a photovoltaic installation allows the storage of the over-generation of energy during hours of sunshine, to consume this energy in periods of higher demand where at the same time the price of energy is higher [52].

Andoni Saez-de-Ibarra et al. propose the use of second life batteries in cooperation with Photovoltaics (PV) renewable energy in a residential environment with the aim of reducing the cost of the electricity bill while decreasing the investment expense owing to the minor costs of second life batteries. The simulation has been done with real photovoltaic generation and electricity consumption curves, together with prices from the Spanish electricity market [53]. *Hanjiro Ambrose et al.* also tested the performance of these second-life applications, but now, in a rural environment where they showed that second-life batteries have twice the life expectancy in applications with photovoltaic systems than current lead-acid batteries [54].

Canals Casals et al. propose six possible uses for second life batteries: energy storage systems connected to the electricity grid or to renewable energies, installations isolated from the grid, services for managing demand from the electricity grid, reuse in portable devices and supporting systems for rapid charging of electric vehicles. But in contrast, from a purely economic point of view, and according to the authors, none of the detailed cases are presented as an interesting application for investment due to the high cost of the batteries [55]. As shown in Figure 3.2, the price of batteries per kWh in 2020 is 200 €. Although, it is expected that this price will continue to fall to a figure close to 100 euros by 2030. For that reason, *Wen-Chen Lih et al.* stress the importance of reusing batteries in the second life, to help reduce their price in both the first and second lives [56].

Apart from the battery cost, battery ageing is crucial to determine the economic viability of a SESS. *J. S. Neubauer et al.* conduct a techno-economic study where they consider the degradation of batteries both during the use of the battery in the vehicle and in the second life in stationary applications. They consider that the use of second life batteries is more profitable than the new one, but there's still a lot of margin for improvement when it comes to ageing. Their findings reveal that a SESS serving for an Uninterruptable Power Supply (UPS) can obtain a payback period of less than 7 years [57]. *Uttam Kumar Debnath et al.* study the costs of using these batteries in their second life in a SESS environment. They also introduce a model to determine the best option to reuse the batteries considering their current state and the use that will be given to them. They determine that the most important factors in the loss of battery capacity are the discharge cycles, operating temperature, ageing, as well as the size and chemistry of the batteries [58].

3.3 Battery ageing

The study of battery ageing is an essential pillar to the successful development of them, both in automotive and stationary applications due to it generating both capacity loss, resistance augmentation and loss of available peak power. As a result, battery ageing is a very complex phenomena not always predicable and strongly dependent on operating conditions that can be divided in:

- **Calendar ageing**
  Calendar ageing is the irreversible lost capacity during storage. In other terms, it is the degradation caused by the battery storage [59]. Self-discharge rate varies highly according to storage conditions. The main condition considering the calendar ageing and self-discharge is the storage temperature. The other principal variable of calendar studies is the State of Charge (SOC) level during storage. Thus, for an equal temperature but for different SOC, cells do not age in the same manner [60]. In many applications, calendar ageing could be the main contributor to battery degradation, since, for example, electric vehicles (EV) are parked 90% of the time [61].

- **Cycling ageing**
  Cycle ageing happens when the battery is either in charge or in discharge. Cycling ageing's factors are function of the battery utilization mode. Calendar-related ageing factors are also included here, because they occur whether the battery is used or not. Apart from these Depth of Discharge (DOD) and C-rate have a direct effect on the cycling ageing [60].

Figure 3.11 presents how the degradation in Li-ion cells originates from an extensive quantity of physical and chemical mechanisms, which influence the different elements of the cells: the electrodes, the electrolyte, the separator and the current collectors [62].

The most common modes of battery degradation are [62]: (see Figure 3.12)

- **Loss of Lithium Inventory (LLI)**
  Lithium ions are consumed by parasitic reactions, such as surface film formation (e.g. Solid Electrolyte Interphase (SEI) loss of LLI: lithium ions are consumed by parasitic reactions, such as surface film formation (e.g. SEI growth), decomposition reactions, lithium plating, etc. and are no longer available for cycling between the positive and negative electrode, leading to capacity fade. Surface films may also no longer be available for cycling between the positive and negative electrode, leading to capacity fade. Surface films may also cause power fade. Lithium ions can also be lost if they are trapped inside electrically isolated particles of the active materials.

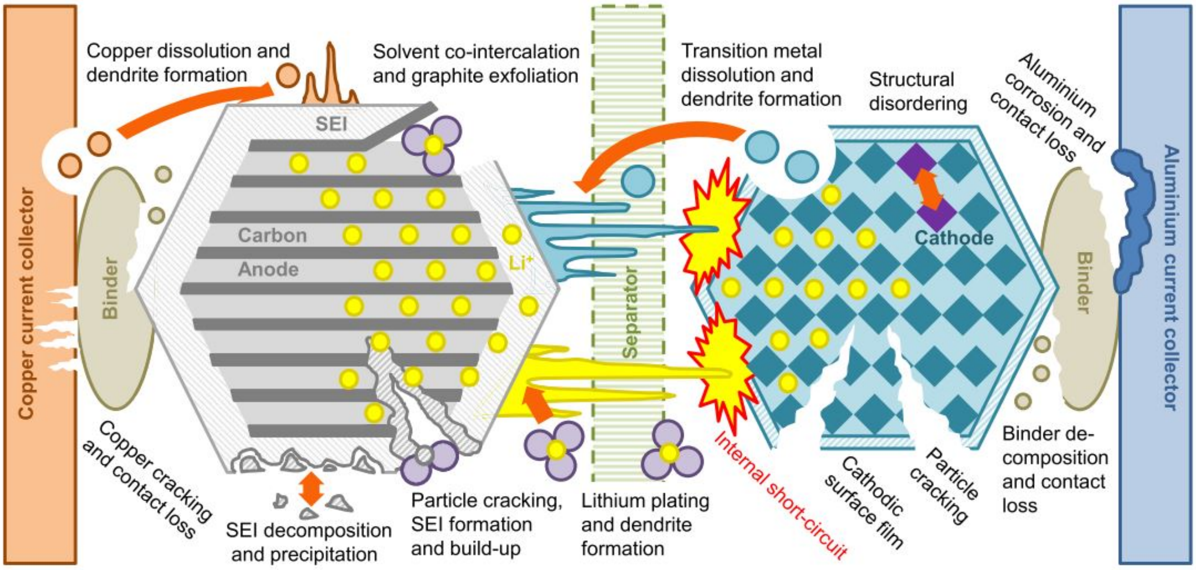


Figure 3.11: Degradation mechanisms in Li-ion cells [62]

- **Loss of active material of the anode**
  Loss of active material of the negative electrode: active mass of the negative electrode (or anode) is no longer available for the insertion of lithium due to particle cracking and loss of electrical contact or blocking of active sites by resistive surface layers. These processes can lead to both capacity and power fade.
- **Loss of active material of the cathode**
  Loss of active material of the positive electrode: active mass of the positive electrode (or cathode) is no longer available for the insertion of lithium due to structural disordering, particle cracking or loss of electrical contact. These processes can lead to both capacity and power fade.

Different methods are used to estimate the State of Health (SOH) of batteries. They are divided into five parts [60]:

- Electrochemical models: detail and model the phenomena occurring inside the battery
- Equivalent electric circuit based models: the battery is reduced as an equivalent electric circuit model
- Performances based models: battery ageing is modelled by physical equations
- Analytical models with empirical fitting: estimation of ageing parameters through measurements
- Statistical approach: approaches mainly based on data, without a-priori knowledge

Ageing tests based on actual application conditions are costly and time consuming. In order to shorten the test and the cost test, most of the battery developers use ageing battery models and accelerate ageing tests [63].

3.3.1 Ageing battery models

Modelling is used to study battery designs and dimensioning in vehicles or in other stationary applications under different working conditions (temperatures, DOD, C- rate, etc.) without

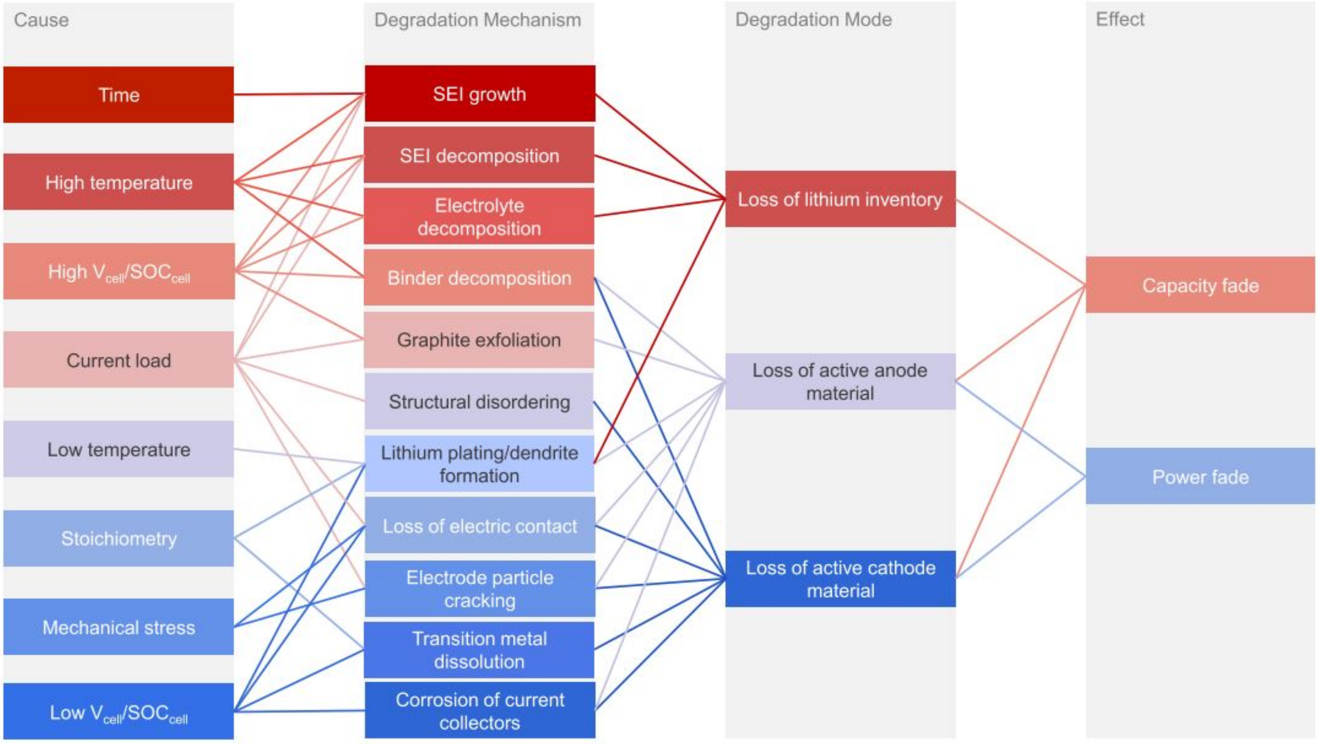


Figure 3.12: Degradation mechanisms in Li-ion cells [62]

the need to perform costly and time consuming experimental tests for each case [64]. In the case of EVs, battery models are useful for practical and real time issues, such as indicating the available range to drivers, or for vehicle design, such as thermal management, lifespan estimation or performance optimization among others [65].

The most used battery models are mathematical, electrochemical or Electrical Circuit Equivalent (ECN), although there are more types such as stochastic and analytical [66]. Battery models for EV applications need a good balance between response speed, reliability and complexity. Electrochemical models are extremely accurate but at the same time extremely complicated, requiring greater data processing capacity [67], therefore, they are not suitable for real-time use in EV. In contrast, ECN are much less complex. Their rapid response gives them the opportunity to work in real time conditions, making them suitable for working in the automotive environment.

One of the main issues in battery modelling is SOC estimation, which in Li-ion batteries is preliminary done by Coulomb counting and voltage reading. Coulomb counting registers the amount of current passing through the battery and it can be applied while the battery is in use. However, measurements have an error that increases over time. Therefore, whenever the conditions are stable enough, SOC estimation is calibrated by means of a voltage measurement.

The ageing of Li-ion batteries has given rise to hundreds of studies, papers and doctoral theses [68][69] but there are very few which study it during their second life and most of these are terminated when the cells have lost only 20 to 30% of their SOH [70][71] with even fewer studying ageing when batteries are actually found in their second life [72][73]. Second life usage of batteries can extend battery lifetime, however the ageing pace of the battery for second life application is unknown [41].

For this reason, during the second life it is also very important to have an equivalent electrical model that indicates the operation and ageing of the batteries. The model allows to know how the cells will age depending on the use they will have in the new application. With the current curve and the temperature, it is possible to determine the life expectancy of the batteries in second life applications [72]. This will make it possible to calculate the economic profitability of these new applications.

Although few authors have studied battery ageing using an ECN during the battery second life, we can find some interesting publications, which focus on studying the investment payback time of each of these SESS using second life batteries. For example, *L. Canals Casals et al.* consider that although the price of second life batteries is a fundamental aspect for the viability of any project, they remark that, the life time of batteries not only depends on the number of cycles, but also the working conditions have a very important effect [74].

It is also very important, in order to calculate the economic viability of these projects, to carry out a study of each country's regulations, because what may be viable in one country may not be so in another. *K. Gur et al.* confirm that the use of an SESS to support renewable energy is not the best investment at this time. Both for new and second life batteries. Although, they state that in both Germany and the United Kingdom the use of SESSs will be a growing business in the coming years, in part, thanks to the facilities of the respective governments to use these applications [75]. At this point, very few authors have tested model battery ageing in conjunction with the economic study linked to each use case.

Another problem here is the complexity of obtaining large data due to the time needed to significantly age batteries. Many studies solve this time problem with accelerated life tests, but this methodology has two main drawbacks. First, an accelerated life test is usually done with a bench test. Hence, the impact of all environmental variables occurring in real life conditions is not taken into account, which produces some errors. Furthermore, these methods cannot perform well enough to obtain the same battery ageing as in real life, due to the lower total storage time but also because of the complex interaction between each variable, which was not considered here [60].

3.3.2 Accelerate ageing

The accelerate ageing test consists of over stressing some variables like voltage, SOC level, DOD, temperature, C-rate... in order to accelerate the ageing phenomenon to get results much earlier [76]. A correct selection of the battery stress factors is required to accelerate the desired ageing phenomenon, as well as, not to introduce additional ageing phenomena, which are not present in real operating conditions. The stress factor levels applied to a Li-ion battery have a nonlinear effect on the lifetime of the cells [77]. Figure 3.13 shows the five parameters that influence the ageing of the battery the most. From most to least influence, these are: temperature, DOD, SOC, previous usage and C-rate.

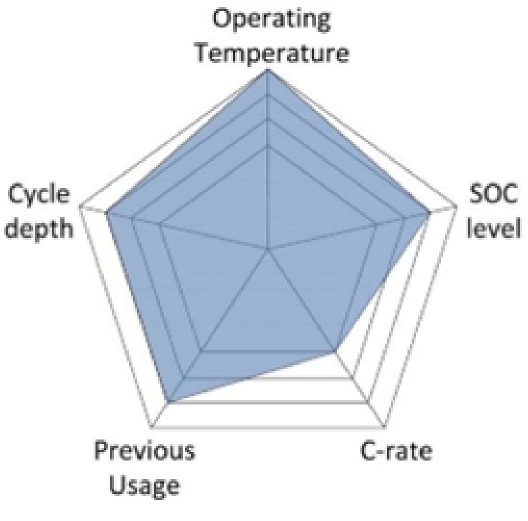


Figure 3.13: Ageing influence of different battery stress factors

The two main stress factors, which influence the calendar ageing of the batteries are the temperature (high or low temperature) and the SOC level (low or high SOC). Instead, the cycling ageing besides the temperature and SOC is also affected by DOD (big cycle depth), and C-rate (high C-rates) [77].

Accelerated ageing tests are performed to validate the estimation performances over the lifetime of an automotive-high-energy-type battery [78].

Accelerated life tests have two main drawbacks. First, an accelerated life test is usually done with a bench test. Hence, the impact of all environmental variables occurring in real life conditions is not taken into account, which produces some errors. Furthermore, these methods cannot perform well enough to obtain the same battery ageing as in real life, due to the lower total storage time but also because of the complex interaction between each variable, which was not considered [60].

3.4 Disassembling

One of the first problems that appears when you want to reuse an electric car battery, is the diversity of models of electrified cars in the market, and with it, of battery manufacturers where each one uses different types of cells, chemistry, communications, cooling system, package [79]. All this makes it very complicated to assemble in the same second life application cells from different manufacturers, different type or different chemistry. Furthermore, if the SOHs in the cells are different, the total capacity of the assembly will be determined by the cell with the lowest SOH, thus reducing the total capacity of the system.

In addition, another interesting point to consider is whether it is better to reuse the batteries directly, or to dismantle them and use the battery modules. Both strategies have advantages and disadvantages [80]. *L. Canals Casals et al.* introduce the two main strategies for second life applications. The first one, using the battery directly, entails simplicity in its handling. With a visual inspection, and a measurement of its SOH as marked by the European Directive 2006/66/EC [29], it can be used again. Whether the entire battery is used or not, some form of electronics and/or software will have to be developed to allow its use in non-automotive applications. This could be taken into account in the manufacture of the battery in order to facilitate this adaptation, therefore an adaptability study of the battery is needed.

On the other hand, the second strategy proposes dismantling the battery and using only the modules that make up the battery, which will require more handling time. In this case, it will be necessary to develop specific electronics and software for the second life application that can be replicated. This second strategy allows greater versatility in defining and creating new energy storage applications using second life batteries [19].

So far, few studies have thoroughly analysed which of the two strategies is better and which are the most economically viable systems of adaptability to second life. *K. Wegener et al.* study the disassembly of the battery of an Audi Q5 and detail each of the stages to be followed and all the components that make up the battery. The complete disassembly of a battery is demonstrated [81]. Under other circumstances, *L. Canals Casals et al.* go into more detail and determine that for the moment the use of modules is not economically viable since the costs of re-manufacture are very high [79]. *J. S. Neubauer et al.* also indicate the big problem of battery reuse due to the high costs of repair and re-manufacture them [57], so an important point to study would be the reduction of this process, thinking from its manufacture in first life. Therefore, it is very important to reduce these costs in order to make the reuse of batteries economically viable.

Likewise, another point to take into account is that the batteries that are going to be reused, unlike the new ones that leave the factory directly, will be recovered from different places and ways; from different types of vehicles and manufactured by many companies. In Spain, this recovery will mainly take place in authorised treatment centres (CAT), but also in workshops or vehicle dismantling centres. The Spanish law 1383/2002 regulates the management of end-of-life vehicles [82]. Furthermore, another important point to consider is safety. These batteries still have a residual energy inside that can be dangerous, which means that they can only be handled by qualified professionals. The recycling of these batteries must be carried out in accordance with the European Directive 2006/66/EC [29] and the Spanish Law 710/2015 [83].

Chapter 4

Objectives

The major difference between a thing that might go wrong and a thing that cannot possibly go wrong is that when a thing that cannot possibly go wrong goes wrong it usually turns out to be impossible to get at and repair.

Douglas Adams.

The main purpose of this thesis is to analyse in detail all stages from the moment the Electric Vehicle (EV) battery is removed from the car until it is recycled, as well as identify innovative business opportunities that enable car manufacturers to put electric vehicles on the market in a more cost-effective way. To achieve this goal, the research is divided into more concrete objectives, which are as follows:

1 **Determine the EV battery disassembling activities cost:**
From an economic point of view, the whole process of the battery disassembling is examined in detail. First, the battery is removed from the car, then it is analysed to determine its performance and health condition. Secondly, the battery is removed at module level and then at cell level. The goal here, is to determine at what level of dismantling it is most feasible to reuse the battery, taking into account the cost and time of dismantling.

2 **Analyse the economic viability of a battery treatment centre in Spain:**
In order to have a complete economic analysis of the disassembling activities, setting up a factory in Spain is analysed, based on the EV sales forecast of the coming years.

3 **Design a battery ageing economic model:**
Starting from an existing battery ageing model, the aim is to improve it including an economic simulation capable of determining if the Return of Investment (ROI) of any

possible Stationary Energy Storage System (SESS) comes before the batteries reach the end of their 2nd life.

4 **Validate through real cases the economic model:**
Identify use cases and potential customers of the SESS. To do so, two real scenarios are introduced in the economic model to validate the model performance. The model is capable of optimizing any electrical consumption from an economic point of view with the use of an SESS always taking into account the battery ageing.

5 **Implement a second life battery project:**
In order to demonstrate the technical and economic feasibility of a second life battery project, a SESS is installed in a house, together with solar energy panels, so as to reduce the electricity bill as much as possible.

6 **Compare Lithium-Sulphur and Lithium-ion batteries from an electro-mobility point of view:**
Contrast the current battery technology (Lithium-ion batteries) and the most promising at the moment, Lithium-Sulphur. Both technologies are analysed to determine the main differences between both, including battery modelling, environmental analysis and cost.

Chapter 5

Methodology

The language of experiment is more authoritative than any reasoning: facts can destroy our ratiocination—not viceversa.

Alessandro Volta.

Once the objectives of the thesis have been defined, this chapter focuses on the research methods used to achieve them.

Firstly, the procedure followed to carry out the battery disassembly will be explained. This approach will help us to analyse the different processes, times and costs, in order to prepare the battery for a 2nd life. Next, the location of a battery treatment centre in Spain to prepare them for second life will be analysed from an economic and strategic point of view.

Subsequently, based on a battery ageing model, a new economic model has been developed. This model is able to calculate the savings that the installation of a Stationary Energy Storage System (SESS) causes determining its capacity and taking into account the battery ageing. Following, its operation will be validated and the procedure to calculate the economic viability of installing a SESS will be applied in various case studies. Later, the steps followed to implement a real project with second life batteries are explained in detail.

In addition, an analysis of potential short-term batteries as lithium-ion substitutes has been carried out. In consequence, a full comparison between Lithium-Sulphur and lithium-ion batteries applied to electro-mobility is implemented.

Finally, to conclude this thesis, in Chapter 12, a reflection of all the previous chapters will be discussed and future research will be examined.

5.1 Disassembling process

This study aims to determine at what level of dismantling it is most economically feasible to reuse the battery. Therefore, an advanced research work was conducted in Chapter 6 using the disassembly of the Smart Forfour battery. Figure 5.1 presents the battery's characteristics. To achieve this objective, the battery was submitted to a full disassembly process, from battery to cell and the account in terms of time and cost of each operation was registered. This process is extremely important because regardless of the second use of the battery, the disassembly is an inevitable process [84], together with a proper and specific testing in each case [85] due to it having to ensure the good performance of those batteries as if they were new [86].

Energy	17,6 kWh	**Capacity**	52 Ah
Voltage	339 V	**Modules**	3
Cell configuration	96s1p	**Weight**	169 kg
Cooling	Liquid	**Range**	90 km

Figure 5.1: Process of disassembling the battery from de car

The disassembling process has been carried out at Universitat Politècnica de Catalunya – BarcelonaTech (UPC) facilities, during the year 2019. This process has been done manually as nowadays no automatization of the process is available due to the non-standardization of the batteries packaging.

In fact, the standardization of the batteries evaluation process is object of further interesting studies as indicated by *Ruiz and Di Persio*, but this is out of the scope of this thesis [39].

Figure 5.2 shows the four disassembling steps that will be examined in detail in Chapter 6.

To evaluate the economic aspects of the disassembling, labour cost and time has been accounted using the following assumptions:

- Engineer labour cost = 50 €/hour [87]
- Facilities costs have not been included
- Machinery nor electricity cost has been considered as they are considered as standard hand tools with minimal consumptions
- The appropriate work safety conditions tools have been employed following the Regulation Nº 100 of the Economic Commission for Europe of the United Nations (UNECE)[88].

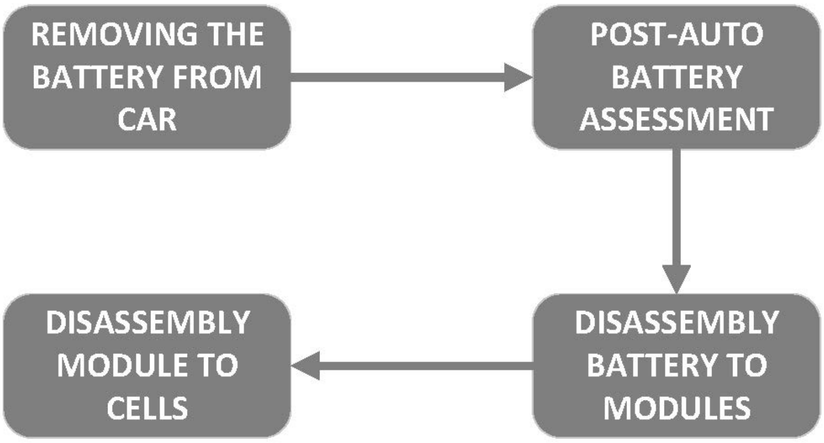


Figure 5.2: Process of disassembling the battery from de car

5.2 Battery treatment centre

For the purpose of determining the economic feasibility of establishing an industrial plant for battery handling to prepare them for a 2nd life or recycling in Spain, firstly, the main key players in Europe will be identified. Collection and transport, disassembly, 2nd life and recycling will be the processes that will be assessed. In addition, its geographical location will be analysed, as today, most of the battery treatment and recycling centres are located in the centre of Europe [89].

For that reason, Chapter 7 makes a comparative cost study of having a battery treatment centre in Spain or transport the batteries to Germany to be treated there. In order to define the most optimal solution, several economic, environmental and social factors will be taken into consideration. Following, all the premises considered for the study will be explained.

First of all, Electric Vehicle (EV) sales in Spain are determined. The entire comparison will be based on these volumes. According to *"ANFAC: Asociación Española de Fabricantes de Automóviles y Camiones"*, Table 5.1 shows EV's sales to date and the sales forecast until 2030 [90].

Table 5.1: EV sales and sales forecast in Spain [90]

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
BEV	9.671	15.495	17.711	30.811	48.517	68.035	85.044	106.304	132.881	166.101	207.626	259.532	324.415	405.519
PHEV	3.350	5.686	6.550	22.380	42.764	86.041	146.993	183.742	229.677	287.096	358.870	448.588	560.735	700.918
TOTAL	**13.021**	**21.181**	**24.261**	**53.191**	**91.281**	**154.076**	**232.037**	**290.046**	**362.557**	**453.197**	**566.496**	**708.120**	**885.150**	**1.106.438**

Secondly, the average battery capacity of the EV will be considered as shown in Table 5.2. This estimation was made by the author after visiting several OEM's website and analysing different specialized magazines of the automotive sector. It is possible that the battery capacity prediction from year 2025 is not completely accurate because this technology is constantly evolving. In any case, this fact will not have a considerable effect on the comparison, since as can be seen in the definition of the other premises, very few batteries will be put into operation after 2025, and within the same period they will also reach the end of their life in the vehicle.

Table 5.2: Battery average capacity per year [9]

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
BEV [kWh]	35	35	35	35	35	50	50	50	70	70	70	70	70	70
PHEV [kWh]	15	15	15	15	15	15	30	30	30	30	30	30	30	30

Table 5.3 shows the logistic costs considered in this study. As can be seen, the costs are shown over the period from 2020 to 2030. In addition, transport within Spain and from Spain to Germany is differentiated. An average distance of 500 km has been considered in the first case and 2000 km in the second one. Costs are also differentiated between BEV and PHEV. And the last consideration, refers to the state of the battery. If the battery to be transported is damaged, the cost will be double. These costs have been calculated based on ECOBAT Logistics rates [91] and extrapolated for this case study according to *S. Rohr et al.* [92]. Transport is carried out in a truck that can hold 4 BEV batteries or 8 PHEV batteries. Critical batteries are always transported alone on the truck. Furthermore, to compare the CO_2 emissions in each of the scenarios, and according to *F. Rodriguez*, it has been estimated that these trucks emit 500 grams of CO_2 per kilometre [93].

Table 5.3: Logistics costs [91][92]

		2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
							Spain ⟶ Spain					
BEV SAFE	[€]	400	386	372	359	346	333	322	310	299	288	278
BEV UNSAFE	[€]	800	771	744	717	692	667	643	620	598	577	556
PHEV SAFE	[€]	140	135	130	126	121	117	113	109	105	101	97
PHEV UNSAFE	[€]	280	270	260	251	242	233	225	217	209	202	195
							Spain ⟶ Germany					
BEV SAFE	[€]	600	579	558	538	519	500	482	465	449	433	417
BEV UNSAFE	[€]	1.200	1.157	1.116	1.076	1.038	1.000	965	930	897	865	834
PHEV SAFE	[€]	450	434	418	403	389	375	362	349	336	324	313
PHEV UNSAFE	[€]	900	868	837	807	778	750	724	698	673	649	626

According to *C. Hoyer* [94], and our own investigation with the adjusted version of BatPac [95], Table 5.4 shows the premises used in this study considering the failure and degradation parameters of the battery during its first ten years of use. In addition, the table shows the percentage of batteries that end their life in the car due to warranty failure. The accident rate is shown below with the percentage of batteries that can be reused for second life. The difference will directly go to recycling. In the next row, the batteries that reach the end of their life in a normal way are detailed. The degradation rate of both Battery Electric Vehicle (BEV) and Plug and Hybrid Electric Vehicle (PHEV) is specified. Finally, the total percentage of batteries that will be used for 2nd life and recycling is shown.

Table 5.4: Failures and degradation battery premises

Years	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Warranty failures	0,25%	0,23%	0,23%	0,23%	0,23%	0,23%	0,27%	0,29%	0,32%	0,35%
Accidents rate	0,50%	0,50%	0,50%	0,50%	0,50%	0,50%	0,50%	0,50%	0,50%	0,50%
Qualified for 2nd life	0,30%	0,30%	0,30%	0,30%	0,30%	0,30%	0,30%	0,30%	0,30%	0,30%
End of life	0,001%	0,005%	0,016%	0,047%	0,179%	0,350%	0,697%	1,331%	3,548%	4,529%
BEV SOH degradation	100%	98%	96%	94%	92%	90%	88%	86%	84%	82%
PHEV SOH degradation	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%
2nd life	0,30%	0,30%	0,31%	0,33%	0,42%	0,53%	0,75%	1,17%	2,61%	3,24%
Recycling	0,20%	0,20%	0,21%	0,22%	0,26%	0,32%	0,44%	0,67%	1,44%	1,79%

According to *S. Rohr et al.* [92], Table 5.5 shows the incomes per kWh that both 2nd life and recycling could generate.

Table 5.5: Incomes for 2nd life and recycling

		2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2nd life	[€/kWh]	100	95	90	85	80	75	70	65	60	55	50
Recycling	[€/kWh]	30	30	30	30	30	25	25	25	25	25	25

Another important factor in determining the viability of manufacturing a new battery treatment plant is the investment needed to build a new factory. In this case, and according to *M. Foster*, has been considered an investment of 20 million € in a plant that will be capable of handling 30.000 batteries every year [96]. To allocate the costs of this factory to each year, the straight-line depreciation method will be used, which means an annual cost of 666.667 €. As more than one factory will be necessary to absorb the entire volume of batteries that the Spanish market will generate, this value will be extrapolated according to the needs of each year.

Once, all the premises and incomes are defined, the next step will be to calculated using a spreadsheet, the logistic cost of transport all these batteries that will be reaching the end of their life in the vehicle for one reason or another according to the situations described. This cost will be compared to the possible benefits that these batteries can generate by being reused in a SESS or being recycled. A comparison of the CO_2 emissions generated in both cases will also be made.

5.3 Economic model for 2nd life batteries

Based on a Lithium-ion ageing battery model previously developed by UPC [74], Chapter 8 proposes how to upgrade it in order to calculate simultaneously the battery ageing and the economic feasibility of installing a SESS.

The first model was developed using MATLAB and SIMULINK, for this reason the same software will be used in this new development.

Figure 5.3 shows a schematic drawing of the developed model taking into account temperature, SOC and time to estimate the calendar ageing. In the cycling ageing, a part of the three previous variables, DOD and C-rate are also considered. The model outputs are the internal resistance increase, capacity loss and SOH as well as DOD and cell voltage. Marked in red, are incorporated the new parameters that allow to calculate the economic viability of a SESS. Electricity consumption expressed in kW is introduced as a new input. Energy price, power contracted price and hourly electricity distribution are the parameters used by the model to determine the electricity bill cost and the electric parameters optimized. In addition, the model also takes into consideration all the variables that can influence the price of electricity. Parameters such as variable energy price per kWh, difference in invoicing between working days and public holidays, the two annual time changes and advanced management of power term optimisation have been also introduced. A part from that, the SESS features and cost are introduced as an input, due to the developed model will also determine the best capacity of the battery to maximize the savings produced.

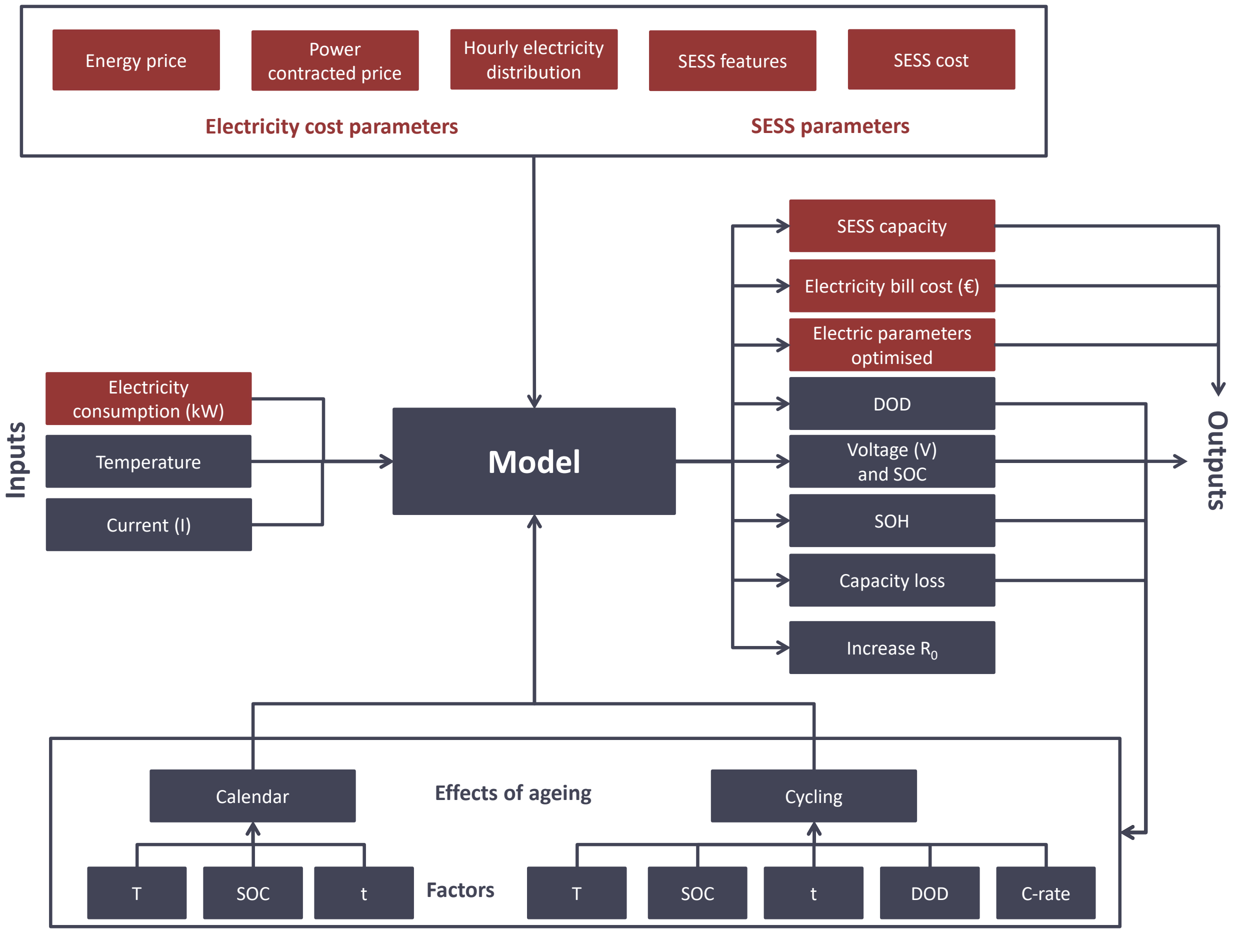


Figure 5.3: Scheme of the simulation model

In order to achieve a reduction in the electricity bill, the economic model will evaluate the impact of installing a SESS using two strategies: energy arbitrage and peak shaving.

- The price of energy changes hourly, which opens up the possibility of temporal arbitrage: buying energy at a low price, storing it, and selling it later at a higher price. To successfully execute any temporal arbitrage strategy, some amount of confidence in future prices is required, to be able to expect to make a profit. In the case of energy arbitrage, the constraints of the energy storage system must also be considered. For example, batteries have limited capacity, limited rate of charging, and are not 100% efficient in that not all of the energy used to charge a battery will be available later for discharge.
- On the other hand, peak shaving refers to levelling out peak use of electricity by industrial and commercial power consumers. Peak shaving is the process of reducing the amount of energy purchased from the utility companies during peak hours of energy demand. Monitoring these power consumption peaks is important not only in terms of power grid stability, but can also affect utility costs. These costs will are usually billed in reference to the maximum peak-load, which means that due to the grid load and amount of power necessary to be produced, costs will be incurred in order to accommodate these peak loads and power requirements. Figure 5.4 shows a graphical example of the functioning of peak shaving.

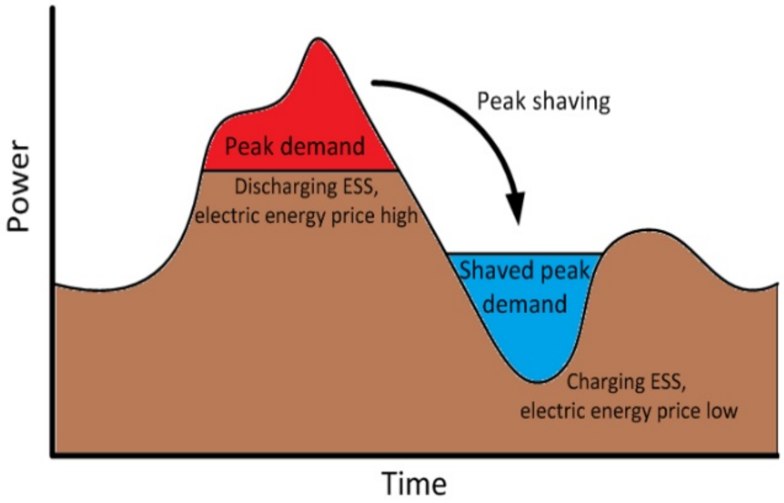


Figure 5.4: Peak shaving example [41]

With the aim of implementing the economic parameters needed to upgrade the model, first of all, a study of the different ways of billing the electricity in Europe was carried out. It has been found that the method of calculation is different in each country. As a result, the calculation model will focus on the Spanish electricity system.

Following, the *"Ley 54/1997"* [97] and the *"Ley 24/2013"* [98], which regulate the electricity sector in Spain, were examined in detail. It was also examined the *"Real Decreto 216/2014"* [99] which establishes the methodology for calculating the costs of electricity for the end consumer in Spain and its legal regime for contracting and the *"Orden IET/2444/2014"* [100] which establishes the fixed regulated costs. Finally, the *"Real Decreto 1164/2001"* [101] establishes, as Table 5.6 shows, the different tariffs available in the Spanish electricity market nowadays, differentiated by voltage level and power contracted.

The proposed economic model, will have as input parameters the electricity consumption expressed in kW, together with the variables of energy price, power contracted price and hourly electricity distribution in order to simulate the electricity bill and calculate the savings that the

Table 5.6: Electricity tariffs in Spain

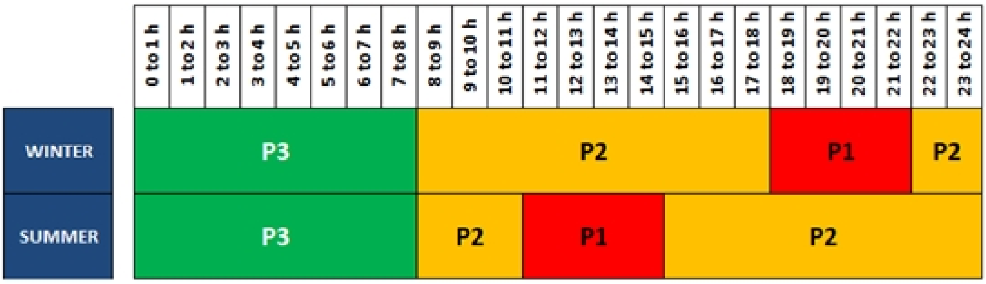
Access Tariff	Power
Low Voltage Access Tariffs	
2.0A, 2.0DHA, 2.0DHS	Up to 10 kW
2.1A, 2.1 DHA, 2.0DHS	Between 10 and 15 kW
3.0A	More than 15 kW
High Voltage Access Tariffs	
3.1A	Less than 450 kW
6.1A, 6.1B, 6.2, 6.3, 6.4, 6.5	More than 450 kW

installation of a SESS causes. The electricity bill in Spain is composed of the following terms: contracted power (in kW), energy consumed (in kWh), reactive energy (in KVAr) and others such as the electricity meter rental and taxes.

The proposed model in this thesis is designed to optimize the contracted power and the energy consumed on all supplies against tariff 3.0A or tariff 6.1A, due to in terms of kWh consumed per year, are the most commonly used. Below, the characteristics of both tariffs are specified together with the calculation methodology that will be introduced in the model.

Tariff 3.0A

General low voltage (< 1 kV) tariff with three periods: P1, P2 and P3 for contracted powers below 15 kW. Each period corresponds to a daily time zone, as Figure 5.5 shows, where the price of energy and power is different. In this tariff a different power can be contracted in each period. In general, this tariff is usually aimed at Small and Medium Enterprises (SMEs), although there are also some cases in which they are also contracted for larger houses.



	0 to 1 h	1 to 2 h	2 to 3 h	3 to 4 h	4 to 5 h	5 to 6 h	6 to 7 h	7 to 8 h	8 to 9 h	9 to 10 h	10 to 11 h	11 to 12 h	12 to 13 h	13 to 14 h	14 to 15 h	15 to 16 h	16 to 17 h	17 to 18 h	18 to 19 h	19 to 20 h	20 to 21 h	21 to 22 h	22 to 23 h	23 to 24 h
WINTER	P3								P2										P1				P2	
SUMMER	P3								P2			P1				P2								

Figure 5.5: Hourly distribution of the tariff 3.0A

The cost of the power contracted in tariff 3.0A is the sum of multiplying the billed power of each of the three periods by its respective price as detailed in Table 5.7. The invoiced power of each period depends on the contracted power and the used power registered by the meter. If the registered power is less than 85% of the contracted power, the 85% of the contracted power will be charged. Instead, if the registered power between 85% and 105 % of the contracted power, it will charge the power used registered by the meter. Finally, if the registered power exceeds 105% of the contracted power, the power used plus a penalty will be charged. Double the difference between the registered value and the value corresponding to 105% of the contracted power as a penalty.

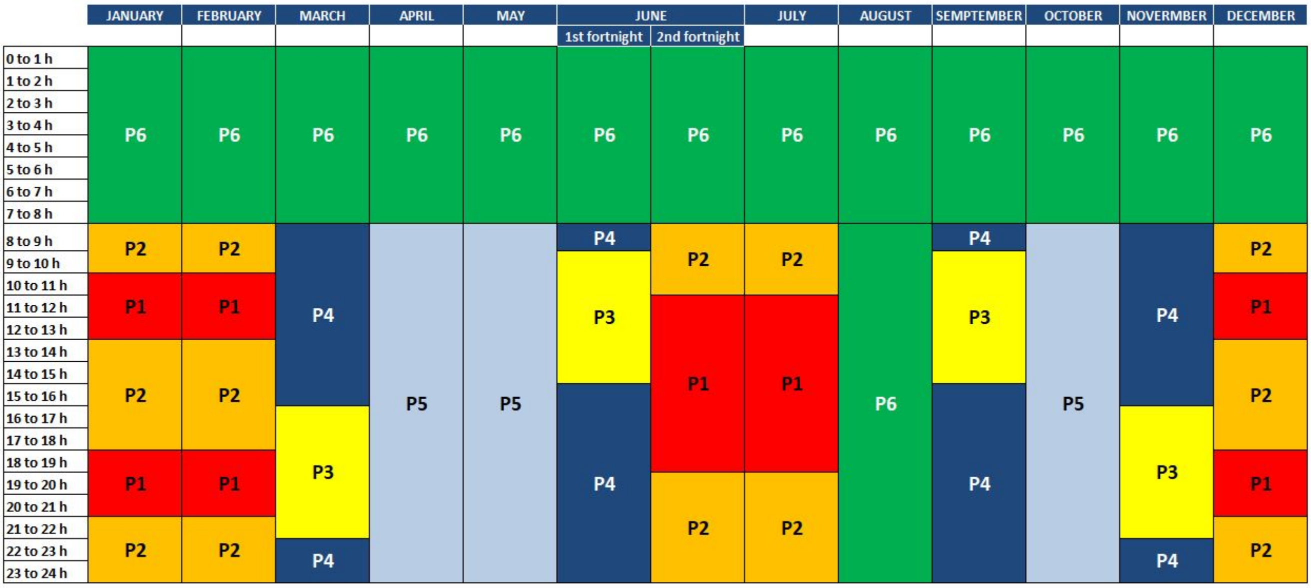
On the other hand, the energy consumed is billed as the sum of the energy consumed in each period for its respective price as shown in Table 5.7

Table 5.7: Tariff 3.0A costs

TARIFF 3.0A	**POWER TERM [€/kW·year]**	**ENERGY TERM [€/kWh]**
Period 1	40,728885	0,111200
Period 2	24,437330	0,090727
Period 3	16,291555	0,066407

Tariff 6.1A

This tariff is applicable to any electricity supply point with six periods: P1, P2, P3, P4, P5 and P6 for contracted power in any of the periods above 450kW in high voltage ($>=$ 1 kV). Each period corresponds to a daily time zone, as Figure 5.6 shows, where the price of energy and power is different.



	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE		JULY	AUGUST	SEMPTEMBER	OCTOBER	NOVERMBER	DECEMBER
						1st fortnight	2nd fortnight						
0 to 1 h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
1 to 2 h													
2 to 3 h													
3 to 4 h													
4 to 5 h													
5 to 6 h													
6 to 7 h													
7 to 8 h													
8 to 9 h	P2	P2	P4	P5	P5	P4	P2	P2	P6	P4	P5	P4	P2
9 to 10 h						P3				P3			
10 to 11 h	P1	P1											P1
11 to 12 h							P1	P1					
12 to 13 h													
13 to 14 h	P2	P2											P2
14 to 15 h													
15 to 16 h						P4				P4			
16 to 17 h			P3									P3	
17 to 18 h													
18 to 19 h	P1	P1											P1
19 to 20 h							P2	P2					
20 to 21 h													
21 to 22 h	P2	P2											P2
22 to 23 h			P4									P4	
23 to 24 h													

Figure 5.6: Hourly distribution of the tariff 6.1A

As in tariff 3.0A, in tariff 6.1A the energy consumed is billed as the sum of the energy consumed in each period for its respective price as shown in Table 5.8.

On the contrary, the way of invoicing the contracted power in tariff 6.1A is completely different from tariff 3.0A. For each of the six tariff periods a power will be contracted, applicable throughout the year. The power billing term results from multiplying the power to be billed in each invoicing period by the corresponding power term, according to the formula 5.1.

$$FP = \sum_{i=1}^{n} t_{pi} \times P_{fi} \tag{5.1}$$

Where:

- t_{pi} = annual price of the power term of the tariff in the period "i" expressed in [€/ kW · year] as shown Table 5.8.

Table 5.8: Tariff 6.1A costs

TARIFF 6.1A	**POWER TERM [€/kW·year]**	**ENERGY TERM [€/kWh]**	**Ki**
Period 1	39,139427	0,101173	1
Period 2	19,586654	0,089755	0,5
Period 3	14,334178	0,079262	0,37
Period 4	14,334178	0,07277	0,37
Period 5	14,334178	0,069834	0,37
Period 6	6,5401770	0,060671	0,17

- P_{fi} = power to be invoiced in tariff in the period "i" expressed in kW.

In tariffs with high voltage, as is the case with the tariff 6.1A, the value of the contracted power in the different periods must comply with the condition that the contracted power in the period (Pn+1) is always bigger than or equal to the contracted power in the previous tariff period (Pn) as shown in equation 5.2.

$$P_{p1} \leq P_{p2} \leq P_{p3} \leq P_{p4} \leq P_{p5} \leq P_{p6} \tag{5.2}$$

If the power registered by the meter exceeds the contracted power in any of the periods, then a billing term is applied for these power excesses, as many times as quarter-hour periods an excess is registered throughout the invoicing period. Thus, the invoicing of excess power for tariffs 6.1A of 6 periods is calculated according to the equation 5.3 established in the *"Real Decreto 1164/2001"* [101].

$$FP_{EP} = \sum_{i=1}^{6} K_i \times 1,4064 \times A_{ei} \tag{5.3}$$

Where:

- K_i = coefficient that will take the following values depending on the tariff period.
- A_{ei} = shall be calculated according to the following formula 5.4

$$A_{ei} = \sqrt{\sum_{j=1}^{n} (P_{dj} - P_{ci})^2} \tag{5.4}$$

Being:

- P_{ci} = contracted power in period "*i*" considered.
- P_{dj} = power demanded in each of the quarters of an hour of the period "*i*", in which P_{ci} has been exceeded.

Once the improvement of the model has been made, with the integration of the economic viability method, a validation of the model is carried out in Chapter 9 analysing the economic impact that has the installation of a SESS using batteries in their second life in real scenarios taking into account the battery ageing.

In 2018, SMEs generated 65.9% of total employment in Spain, similarly to that of the European Union average [102]. Consequently, this simulation focuses the analysis on SMEs considering a company of the industrial sector and a company of the hotel sector. The details of the whole calculation process are presented in Chapter 8, indicating how it determines the feasibility of installing a SESS from the point of view of the battery ageing and the economic return.

Appendix.A shows the MATLAB script where the hourly distribution of electricity tariffs are established. In addition, in Appendix.B public holidays are indicated. The two annual time changes are indicated in Appendix.C as an hour difference can significantly vary results. Furthermore, other scripts of the economic model are also included in the appendix.

5.4 Implementation of a 2nd life battery project

Among the different business models determined around the SESSs, one of the most interesting and that could set future trends, would be a domestic installation. This business model has been demonstrated at theoretical level. Therefore, when the technical and economic viability of the installation of a SESS has been proved through simulations, the second life batteries should then be implemented in a real project. As a result, in Chapter 10, an installation in a domestic environment where the second life batteries will work together with solar panels in order to lower the electricity bill has been set up. In addition, if necessary, the results obtained will help to improve the accuracy of the economic simulation model.

The facility, located in La Sénia (Spain), consists of fourteen 370 Wp monocrystalline solar modules, as shown Figure 5.7, making a total of 5,18 kWp installed together with a 2nd life battery of 8 kWh capacity. Figure 5.8 shows a basic outline of the proposed installation.

The design and calculation of the installation was carried out as part of this doctoral thesis. The electrical installation of the solar panels was carried out by an external company and the second life battery has been bought from the company BeePlanet Factory [103], the first company in Spain which re-configure and adapt EV batteries to be converted into a SESS.

In Chapter 10 the proposed electrical installation is detailed. In addition, from the first data obtained from the installation, the real economic results are presented and compared with those calculated in the designed model.

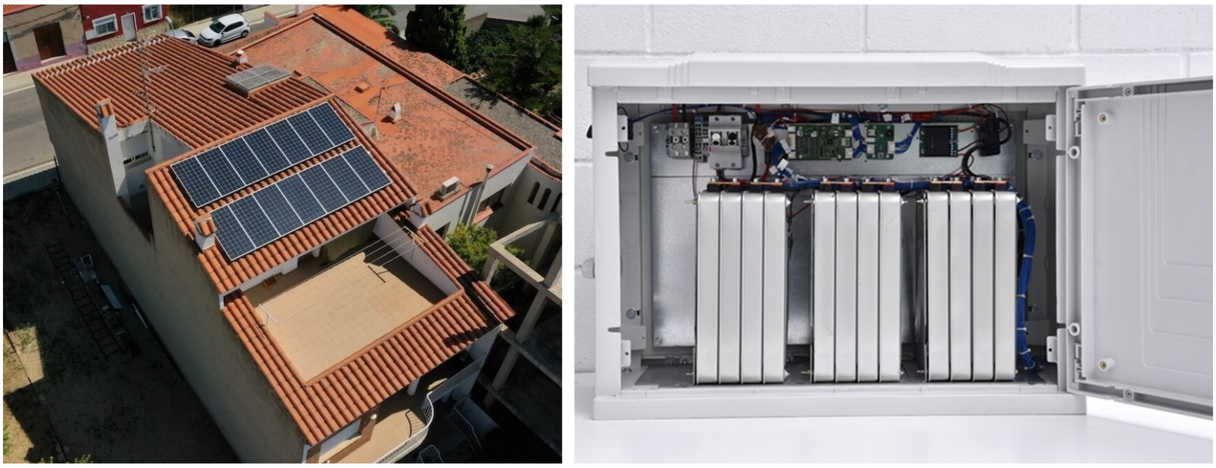


Figure 5.7: Left: Photovoltaic panels. Right: Battery 2nd life

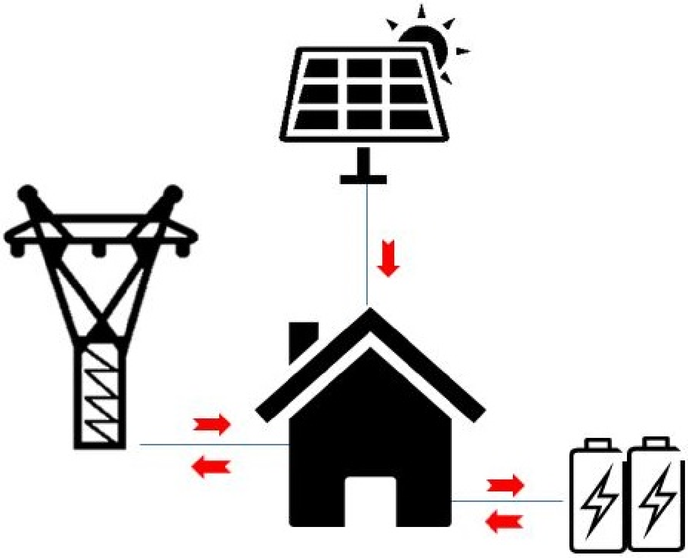


Figure 5.8: Schematic installation diagram

The project has been implemented according to the current regulations in Spain:

- Low Voltage Electrotechnical Regulations according to the *"Real Decreto 842/2002"* [104] where the regulations to be complied with regarding the electrical installation are established.
- *"Real Decreto 1627/1997"* [105] which lays down minimum health and safety requirements for construction sites.
- *"Ley 54/1997"* [97] and *"Ley 24/2013"* [98], which regulate the electricity sector in Spain.
- *"Real Decreto 900/2015"* [106] which regulates the administrative, technical and economic conditions for the supply of electricity for self-consumption and for production for self-consumption.
- *"Real Decreto 661/2007"* [107] where the activity of electricity production under a special regime is regulated.

5.5 Comparison of Lithium-Sulphur and Lithium-Ion batteries

EV use mostly Lithium-Ion batteries but this technology is reaching its theoretical limit (200–250 Wh/kg) [108]. Consequently, it seems very difficult for this chemical variant to meet the needs of EV customers in terms of driving range. At the moment, everything indicates that the best placed variant to replace the Li-ion batteries is Lithium-Sulphur. As a consequence, this chapter will analyse, in detail, the difference between these two chemical variants.

The literature research was conducted using two main databases, Scopus and Web of Science using the search terms: “Li-S”, “battery” and the Boolean “AND” that found 5.065 articles. Filtering by engineering topic the results drop down to 2.740. Although, as it can be observed in 5.9 (left) the topic with more results is chemical with 4.049. This search was repeated using “Li-Sulphur” AND “batteries” with the different possible combinations; no new articles were identified.

An advanced search using the terms “battery”, “Li-S” AND “model$” showed a total of 373 articles Figure 5.9 (right). Notice that the total articles published between 2014 and 2020 is 4.949, as shown Figure 5.10 (left) which represents 90% showing that the research in this field

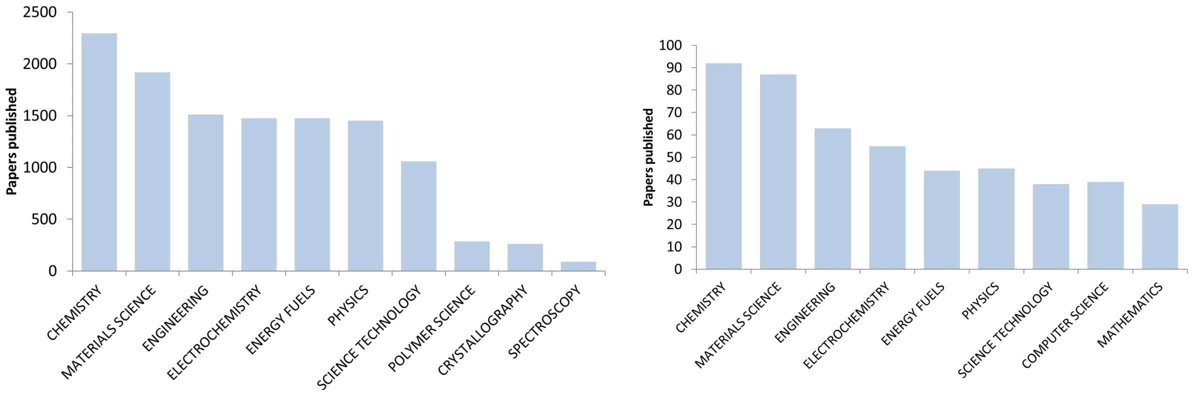


Figure 5.9: Li-S battery papers published filtered by topic (Left). Li-S battery modelling papers published filtered by topic (right)

is very recent [109]. Separating by engineering topic the results are 63 articles (17%). No less remarkable is that filtering by chemistry and materials, results rise up to 47% (179 articles), showing that most of research is still working on the basics of the technology rather than in possible applications. Observing Figure 5.10 (right) it is also interesting to remark that China, USA, South Korea and Germany are the countries with more publications with 65%, 15%, 5% and 3% respectively, coinciding with the countries where EVs development is more advanced and also, where more electric cars are sold [110].

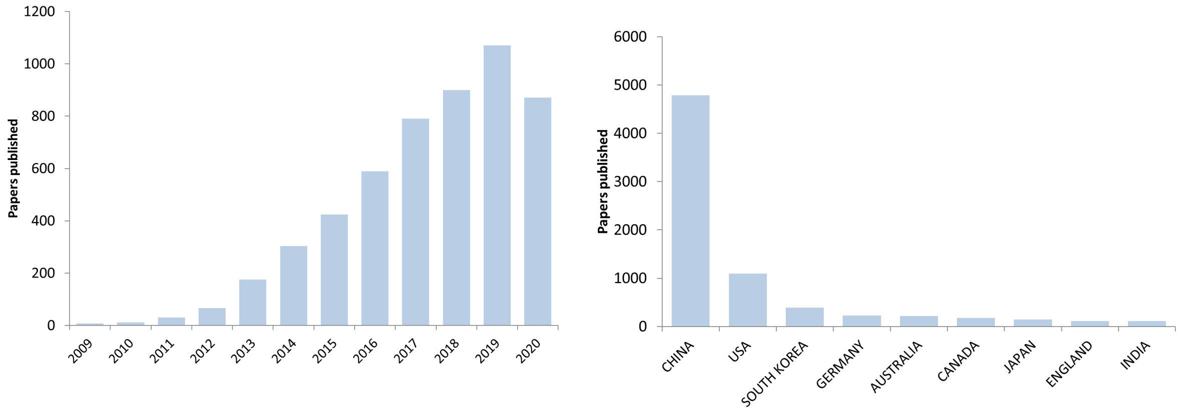


Figure 5.10: Evolution of Li-S publications by year (Left) and distribution per country (Right)

This bibliometric analysis will allow us to identify the current state of both Li-ion and Lithium-Sulphur (Li-S) batteries in order to develop a comparison. Moreover, in Chapter 11 the most appropriate method for battery modelling according to each technology is determined as well as the environmental impact of Li-S against most relevant Li-ion battery technologies is contrasted.

Furthermore, an economic analysis is also performed. This investigation has taken the prices of the principal elements used in highest performing commercial Li-ion batteries comparing them against Sulphur. Prices were collected for the last seventeen years from the USGS National Minerals Information Center databases.

Chapter 6

Economic analysis of battery disassembling activities

You've achieved success in your field when you don't know whether what you're doing is work or play.

Warren Beatty.

6.1 Introduction

Electric Vehicle (EV) are increasingly being used in mobility services. However, the high costs of their batteries, and thus of the vehicles, represent a real barrier that prevents consumers from buying EVs. In order to reduce the EVs costs, research on recovery battery being reused in a second life for stationary use is being explored. This is expected to bring down the cost of these batteries. For this purpose, specific conditioning (disassembling and repurposing) activities on the battery need to be undertaken to enable a further use of Li-ion batteries once they have completed their duty life in a vehicle (first life). Since price matters, the economic aspects of these activities need to be analysed to fully understand the economic feasibility of the second life as a key element to that will determine the success of the implementation of EVs.

This chapter investigates the current state of the disassembling activities by analysing the Smart ForFour Li-ion battery. It also provides insights into the costs of each disassembling operation, from battery level to cell level. Another key aspect will be the remanufacturing at battery level as it presents some advantages over either module or cell level such as a less time is required for the dismantling and consequently a fewer cost.

On the other hand, the reuse at module level presents interesting advantages such as the chance to design more versatile and scalable solutions, which could be more interesting despite their initial drawbacks for many second life applications. Therefore, the disassembling costs will play an important role in the repurposed battery selling prices.

This chapter analyses these conditioning activities and provides insight into the economic aspects related to these operations to illustrate the potential economic benefits derived from the use in a second life of EV Li-ion batteries. The specific case study regarding the adaptation activities of the battery from the Smart ForFour vehicle is reported.

For this purpose, this study aims to reply to the following questions:

- What are the required repurposing operations (adaptation) to re-use automotive batteries into a stationary application?

- What is the cost associated with these activities?

To answer to these questions, an exhaustive empirical analysis of potential disassembly activities on the Smart ForFour battery has been executed, from battery to cell, and the cost of each step has been calculated.

6.2 Disassembling battery process. Conditioning activities

Figure 6.1 shows the complete life cycle of an electric car battery from the extraction of materials until it is recycled. In addition, the disassembling process has been divided into the four following parts:

A Removing the battery from car

B Post-auto battery assessment

C Disassembly battery to modules

D Disassembly module to cells

The process can change depending on which level of disassembly is needed to reuse the battery and to better suit the new application, as a second life. This differentiation addresses the concerns regarding the potential second life application of the battery, that is to reuse the battery as it is, re-use only certain modules of the battery or re-use only certain cells of the battery (for instance, for small traction applications such as e-skates) [19]. The analysis of the repurposing operations has not been assessed in this paper due to its evaluations being already well known since many authors have investigated this topic [111]

A REMOVING THE BATTERY FROM CAR

The first step in the disassembling consists of removing the battery from the car. This section explains in detail through five steps the process that has been carried out for the removing of the battery from de car, as it can be seen in Figure 6.2.

1 **Vehicle preparation**
The vehicle was put on Neutral mode (no gear is engaged) (N-mode) instead of Park mode (P-mode) so that it could be dragged after the traction battery is removed, and the key was removed from the contact.

2 **Disconnection of service disconnect or Low Voltage (LV) battery**
The first step to guarantee electrical safety was to disconnect the HV battery by means of the service disconnect (manually disconnect the high voltage battery). Since it was

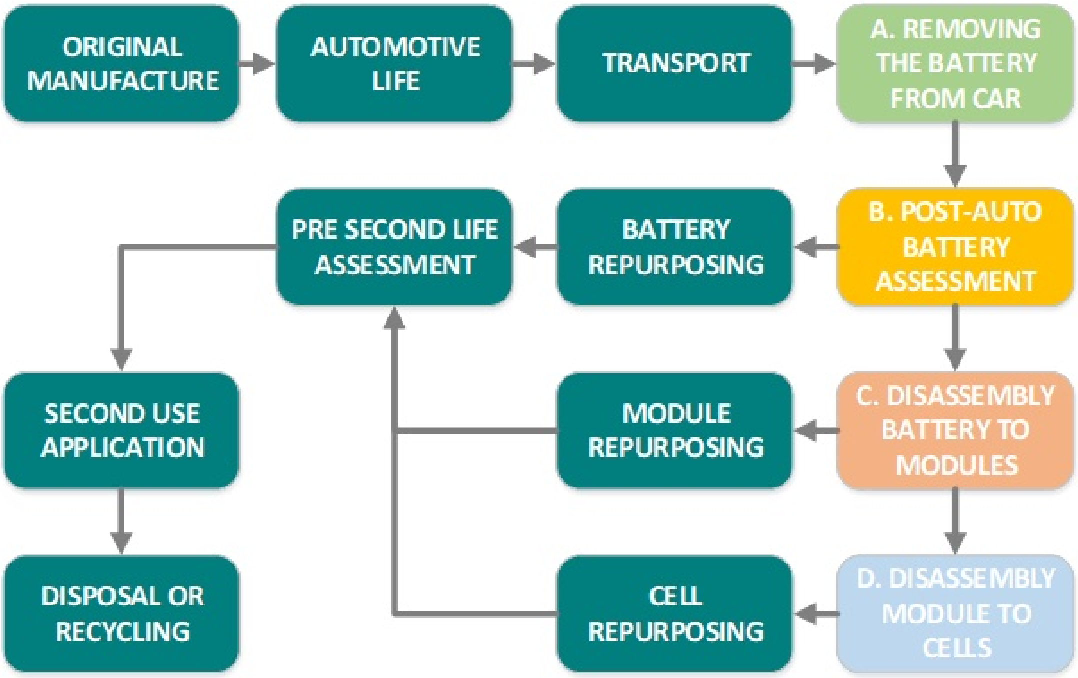


Figure 6.1: Battery life cycle and key analysis steps

Figure 6.2: Process of disassembling the battery from de car

not available or not identified, the LV battery had to be disconnected instead.
After the disconnection of the LV battery, the HV battery kept the LV electric systems on through the DC/DC converter. The car had to be switched to P-mode to stop it. After removing the HV battery, the LV battery was connected again to switch the car back to N-mode.

3 Opening of trunk base

The base of the trunk is a removable plastic cover. Under this cover, the power electronics and the rear traction motor are located. The trunk base was therefore opened to reach the power electronics system.

4 Opening of underside vehicle covers

With one elevator, the underside of the car could be accessed. There were three plastic covers on the underside of the vehicle, the middle one covered the HV battery.
Under the back cover, the HV wiring connecting the control electronics, the DC/DC and the electric motor to the HV battery and the Positive Temperature Coeficient (PTC) heater were located. The cables to the PTC heater went between the top of the HV battery and the platform of the vehicle. A cross-shaped structure reinforced this empty section of the underside of the car against impacts or crashes.
Without the back cover, the battery connectors were visible and accessible. The service disconnect of the HV battery was also accessible after the removal of this cover and under its own foam cover. Figure 6.3 shows the voltage measurement of the battery before being disassembled.
The removal of the service disconnected interrupted the HV pilot line, but did not divide the voltage of the HV battery, so it opened the HV power line just before the

HV connector. No special tools were required to remove the service disconnect and direct contact to non-safe voltage (>60V DC) [88] is easy to access. The removal of the front cover exposed, in addition to others, the HV battery heater, the grounding cables of the HV battery, and the input and output of the HV battery cooling system. The HV battery heater was right beside the HV battery. The HV battery had two grounding cables, one on every side; both had to be disconnected for the removal of the HV battery.

Also on the front side of the HV battery, the pipes of the cooling circuit had to be blocked (to avoid leakage of coolant) and disconnected, then the coolant in the HV battery can be drained. The middle cover is that of the HV battery. The removal of this cover exposed the cooling system on the underside of the HV battery; it consisted of two cooling plates attached to the bottom of the battery package.

Figure 6.3: Battery voltage measurement before being disassembled

5 **Lowering of HV battery**

A lifting platform was used to lower the HV battery from the vehicle. The HV battery rested on a frame secured to the underside of the vehicle. Once the HV battery was safely positioned on the lifting platform, its fixings (6XM18 external hexagonal screws, 3 per side) were removed and the HV battery is lowered. Once the HV battery was removed, the cables over it were accessible.

B POST-AUTO BATTERY ASSESSMENT

This section explains in detail the process of the assessment of the battery once it was removed from the car. The purpose of this post battery assessment is to verify that the batteries conform to the necessary specifications for giving to them a second life.

In contrast to the testing necessary before launching the battery to the market during its first life, the assessment before the second life will be less exacting considering no destructive testing (such as thermal runaway test, over-charge and over-release test) will be applied to the second life batteries because otherwise those batteries to be reused would be destroyed. It must also be taken into account that those batteries will have very different origins, so their SOH and condition will also be very different. Consequently no destructive testing of such sampling would be representative of the batteries' performance. The safety in this case is already proven since all those batteries have already passed demanding approval tests before being used in a car. As a consequence of that, the assessment will be performed is the necessary to guarantee during the entire second life the perfect performance of those batteries under standard the security requirements. Figure 6.4 proposes the necessary tests to be carried out in a total of six steps.

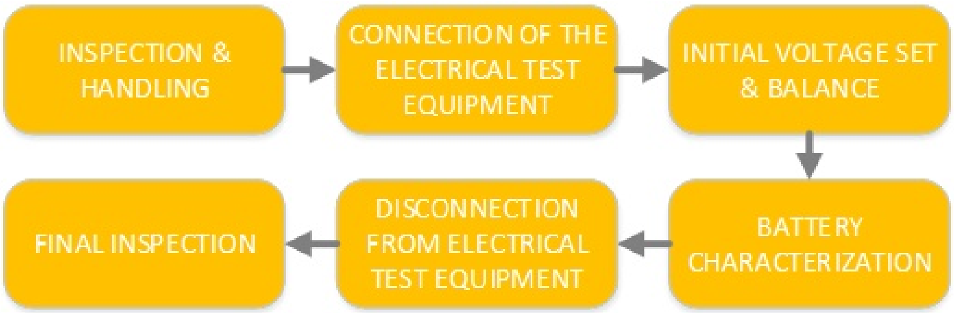


Figure 6.4: Process of post-auto battery assessment

The battery assessment, regardless of the use the battery will have in its second life, is mandatory to determine the current state of the battery. After this point, the battery can be reused directly, or will be disassembled into modules.

1 **Inspection and handling**
Visual inspection of the battery. Check that there is no damaged part and that the following steps can be carried out. All the external damages are checked. As indicated by *Q. Liao et al.* those batteries that have been retired as bulge, weeping and pocking are not suitable for reusing and they should be disassembled for a further recycling and recovery of materials [112].

2 **Connection of the electrical test equipment**
The battery was connected to a battery testing system.

3 **Initial voltage set and balance**
The battery was charged and discharged for the first time to check its condition.

4 **Battery characterization**
A complete characterization of the battery was performed. First of all, the battery capacity was determined. Charge and discharge measurements at constant current were necessary using KRATZER battery test [113]. Following, pulse discharge/charge test was performed. Furthermore, in this step the SOH and the internal resistance of the battery were checked.
In addition, performance tests were made according to the requirements of the use that will be given to this battery in its second life.

5 **Disconnection from electrical test equipment**
The battery was disconnected from the battery testing system.

6 **Final inspection**
After all the tests explained above, a final visual inspection was performed to ensure that the battery is optimal to give it a second life.

C DISASSEMBLY BATTERY TO MODULES

Once the battery has passed all the tests proposed in the post-auto battery assessment, this section explains in detail the process of disassembling the battery up to the modules. As it can be seen in Figure 6.5, the process is divided in nine steps. In the Figure 6.6 the parts of the battery that will be disassembled in this stage are shown.

1 **Removal of package top**
The top and bottom cables of the HV battery enclosure are held together by 31xM14

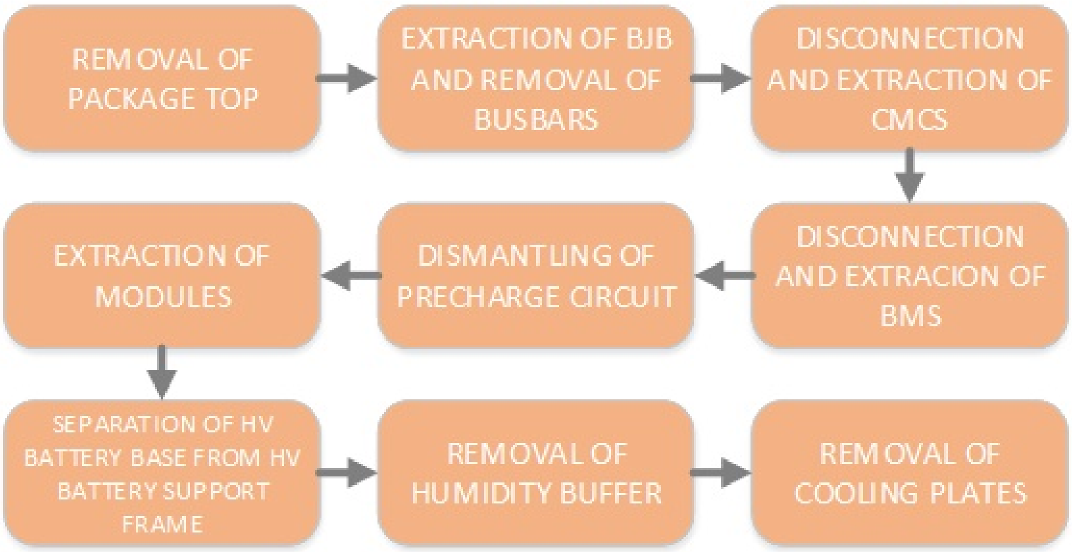


Figure 6.5: Process of disassembly battery to modules

6-lobe external screws (12 on the front, 11 on the back, and 4 on every side) and 52 M8 external hexagonal nuts (17 on the front and the back, and 9 on every side). On the back, two centralizers help on the positioning of the top enclosure. Only screws and nuts hold the two halves of the HV battery enclosure together – there is no glue. The removal of the package top exposed three cell modules connected in series, there CMC's, the BJB, the BMS and the pre-charge circuit.

2 **Extraction of BJB**
The BJB (HV + and HV – relays) are attached to the metallic base of the service disconnect and power connectors. The removal of the BJB required its disconnection from the HV+ and HV- contacts of the battery (both extremes of the series connection of the three modules) and from low voltage wiring. The three modules were connected in series by means of busbars. The busbars were removed.

3 **Disconnection and extraction of Cell Module Controllers (CMCs)**
Each module had its own CMC. After disconnecting their respective sensing and communication wiring, they could be unbolted and removed.
The voltage and temperature sensors of every module send their signals to their respective CMC's by means of the wiring on the side of the module

4 **Disconnection and extraction of BMS**
After disconnecting all the communication wiring from the BMS, it was unbolted and removed.

5 **Dismantling of pre-charge circuit**
At this point the battery pre-charge circuit is disassembled.

6 **Extraction of modules**
The modules are bolted to the bottom of the battery package on both right and left sides. Under each module there is a layer of thermally-conductive paste.

7 **Separation of HV battery base from HV battery support frame**
At this point, the battery base was removed.

8 **Removal of humidity buffer**
At this point, the humidity buffer was removed.

9 **Removal of humidity buffer**
The two cooling plates are bolted to the underside of the battery package. Between

the plates and the package there was a layer of the same thermally-conductive paste found under the modules.

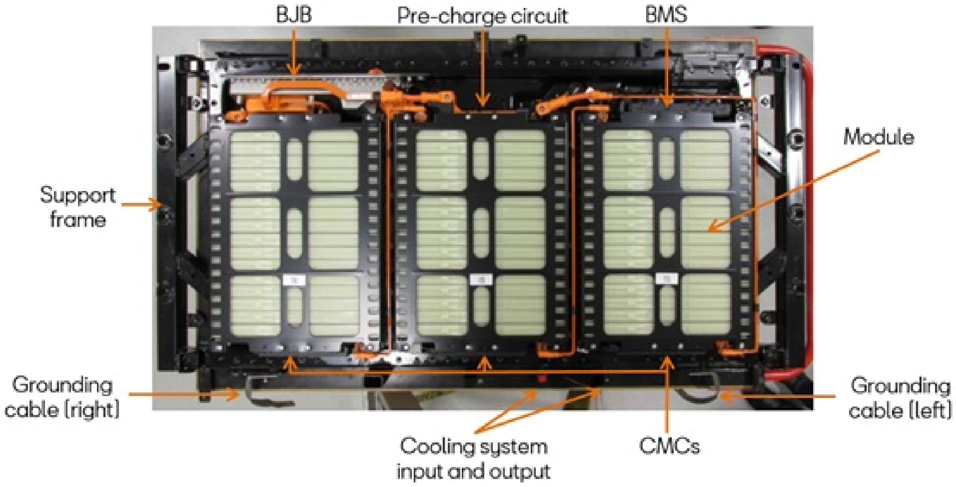


Figure 6.6: Battery parts

D DISASSEMBLY MODULE TO CELLS

The last disassembly step consists of disassembling the battery modules to cells. As it can be seen in Figure 6.7, the process is divided into four steps. This process, although it is not dangerous because of the electrical voltage, requires a lot of precision in the work to be done because otherwise we run the risk of perforating the cells.

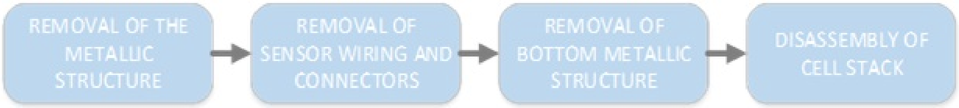


Figure 6.7: Process of disassembly the module to cells

1 Removal of top metallic structure

Before their disassembly, modules were brought to a safe voltage (discharging modules bellow 60V)[88]. Every module consists on a metallic structure surrounding the plates that hold the cells.

The first step to disassemble the modules was to remove the rivets keeping the metallic external structure closed and the bolts fixing the metallic and plastic structures to each other. In order to remove the rivets, they were perforated with drills of progressively larger sizes until they weakened enough to be broken by prying. (See Figure 6.8)

2 Removal of sensor wiring and connectors

On every side of the module, there are fixations for the wiring connecting the cell tabs (on both sides) and temperature sensor outputs (on one side only) to the CMC connector. The wiring fixations were unbolted and removed to expose the soldered terminals. To remove the wiring and its fixations without undoing the soldering of terminals, the wiring had to be cut off on both sides. (See Figure 6.9)

3 Removal of bottom metallic structure

Once the wiring was removed, the last part of the external metallic structure could be removed as well.

Metallic plates are included in every cell carrier plate between cells for better heat

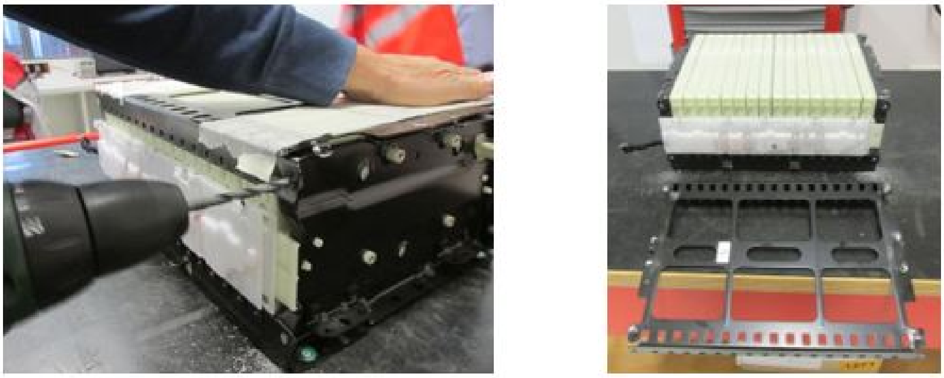


Figure 6.8: Removal of the top metallic cover

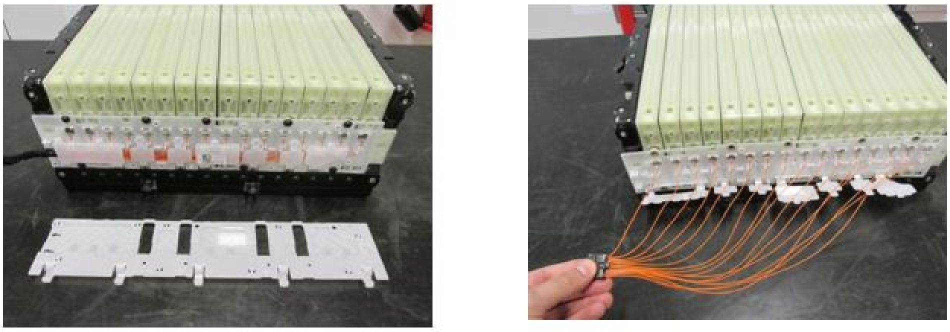


Figure 6.9: Removal of sensor wiring and connectors

dissipation. Their bottom is in direct contact with the thermally-conductive paste under every module. The remaining part of the external metallic structure was removed in the same way as the first part: bolts are unbolted, and rivets are perforated with drills of progressively larger sizes until they weaken enough to be broken by prying.

4 **Disassembly of cell stack**
With the complete removal of the external metallic structure, the cell stack was exposed. The cell stack consists of a series of carrier plates. Every carrier plate houses two cells. In between plates there are three layers of isolating material – one is thick and two are thin. Cell tabs are soldered to each other in series connection.
There were three temperature sensing plates evenly distributed along the cell stack and placed in between plates in the same way as the isolating material layers. Cells were fixed to the carrier plates by means of adhesive tape. (See Figure 6.10)

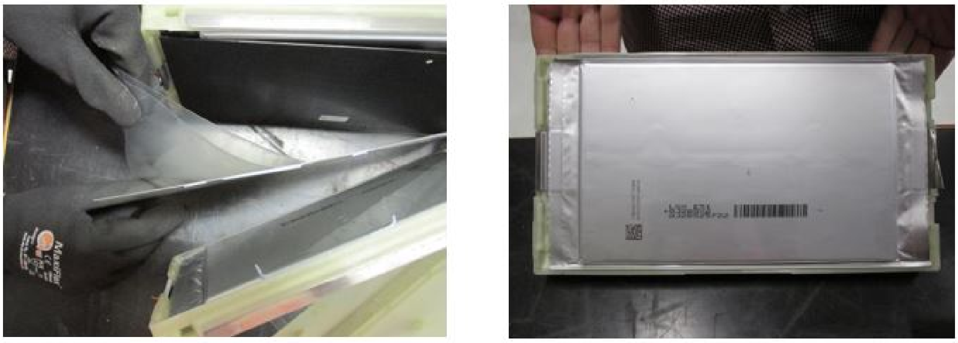


Figure 6.10: Right: Isolation between plates (three layers). Left: Cell on plate

6.3 Results and discussion

This section presents the results obtained of the economic analysis for the complete process of disassembling the battery up the cell level.

Neubauer et al. reports that the cost of conditioning batteries after their useful life in the vehicle deserves special attention. They considered that those costs should be around 60$/kWh for being able to achieve economic profits giving to those batteries a second life [114].

Table 6.1 shows in detail, the human resources labour cost, the required time and the corresponding cost that each activity entails for each operation as described in section 5.1. The most critical point in this section was the removal of all the vehicle covers due to required three people and 30 minutes which makes its cost four times higher than any of the other steps.

Table 6.1: Resources for removing the battery from car

	Human power	**Time [minutes]**	**Cost [€]**
Vehicle preparation	1	5	4 €
Disconnection of service disconnect or LV battery	1	5	4 €
Opening of trunk base	1	10	17 €
Opening of underside vehicle covers	2	30	75 €
Lowering of HV battery	2	10	17 €
TOTAL		**60**	**117 €**

Table 6.2 shows in detail, the human resources labour time and the time needed for doing the post-auto battery assessment with the corresponding cost that this entails. It is easily observed how the characterization of the battery requires more time than any of the other processes. Anyway, this process is key to determining the state of the battery, and cannot be reduced in any case, which will mean at this point we have our greatest expenditure of resources on any battery that can be analysed in the future as well. In this process, there are some activities that with greater automation could reduce some costs regarding the hourly cost of the personnel involved. Since regardless of the level of dismantling required from the battery, this process will be needed, further automation in this process will not affect the difference in cost between the different levels of dismantling.

Table 6.2: Resources for the post-auto battery assessment

	Human power	**Time [minutes]**	**Cost [€]**
Inspection & handling	2	60	100 €
Connection of the electrical test equipment	2	10	17 €
Initial voltage set & balance	1	100	83 €
Battery characterization	1	250	208 €
Disconnection from electrical test equipment	2	10	17 €
Final inspection	2	10	17 €
TOTAL		**440**	**442 €**

Table 6.3 shows in detail, the human resources labour time and the time needed for disassembling the battery to modules. In this process the whole battery is disassembled and the three modules of which this battery consists are obtained.

Table 6.4 shows in detail, the human resources labour time and the time needed for disassembling the battery to modules. In this process only the disassembly of one of the three modules

Table 6.3: Resources for disassembling the battery to modules

	Human power	**Time [minutes]**	**Cost [€]**
Removal of package top	2	30	50 €
Extraction of BJB	2	45	75 €
Disconnection and extraction of CMCs	2	45	75 €
Disconnection and extraction of BMS	2	30	50 €
Dismantling of pre-charge circuit	2	30	50 €
Extraction of modules	2	60	100 €
Separation of HV battery base from HV battery support frame	2	20	33 €
Removal of humidity buffer	2	20	33 €
Removal of cooling plates	2	20	33 €
TOTAL		**300**	**500 €**

obtained in the previous step is considered. If you want to know the cost of dismantling the three modules, you only need to multiply the results of Table 6.4 by three. Note that all the sub processes of this stage have a very similar cost because it is a very manual procedure where it is very difficult to automate some parts.

Table 6.4: Resources for disassembling the module to cells

	Human power	**Time [minutes]**	**Cost [€]**
Removal of top metallic structure	2	60	100 €
Removal of sensor wiring and connectors	2	30	50 €
Removal of bottom metallic structure	2	45	75 €
Disassembly of cell stack	2	30	50 €
TOTAL		**165**	**275 €**

Table 6.5 shows the cost comparison between the different levels of disassembly that we have carried out; battery, module or cell. As it can be seen, the cost at battery level is half the cost at module level. On the other hand, the cost at cell level increases by approximately 25% plus the cost at module level.

Table 6.5: Battery, module and cell cost for the disassembly process

	Battery	**Module**	**Cell**
Removing the battery from car	117 €	117 €	117 €
Post battery assessment	442 €	442 €	442 €
Disassembly battery to modules		500 €	500 €
Disassembly module to cells			275 €
TOTAL	**558 €**	**1.058 €**	**1.333 €**
COST / kWh	**32 €**	**60 €**	**76 €**

Tables above have reported the costs of each disassembly activity. As previously stated, this study considers the first half of the repurposing, the disassembly part only. Surprisingly, in this specific case, the module level and cell level disassembly cost is equal to or higher than that proposed by *Neubauer et al.* [114].

As outlined *Neubauer et al.*, if the automotive and battery OEMs would include the possibility of on-board diagnostic capabilities to understand the capacity of the batteries and would agree to share this information with the companies responsible for battery repurposing it would be much faster and easier to determine if those batteries are valid to give them a second life having a direct consequence in reducing the cost of post-auto battery assessment [114].

Apart from the cost differences explained above, following are some other interesting conclusions we have obtained by the completely disassembling of the Smart ForFour battery.

Batteries with fewer modules reduce the amount of components, consequently this means that the cost of disassembling is going to be much less although on the other hand these modules will have a voltage higher than 60V and can only be handled by personnel accredited to work with HV systems.

One possible serious safety issue to take into account from the battery analysed is that the service disconnect can be reached and used with no need for special tools despite the fact that it gives access the whole voltage of the battery ($U>60V$, usage voltage).

The repurposing at battery level, apart from being more convenient and lower-priced than the other options, presents additional advantages such as the chance to re-use the BMS. However, this option has some disadvantages. A big battery manipulation is required and this step implies complexity in terms of safety, machinery and ergonomic aspects. Furthermore, an additional electronic interface between the battery and the new applications would be required since the communication protocols that vehicles are different from the ones used in SESS.

At module level, more versatile and scalable solutions are possible with an easier connection to increase capacity and power. In this case, as the original BMS will not be used, although the cost of the final application will increase, an optimized BMS can be designed for such use and this will improve the operation of the SESS. The fact that fewer components of the original battery will be employed in this second life will imply lighter SESS. Seemingly like the reuse at battery level, the reuse at module level also has some drawbacks like more handling and preparation time, higher costs, the requirement of designing and manufacture a new cover for the SESS and more time for module diagnosis. Apart from the difficulty in obtaining modules with similar capacities for matched strings.

Therefore, whether a reuse is made at battery level or module level, it is important to find a balance between the repurposing costs and the versatility and the revenues of the different possible final solutions.

Even though the environmental aspects related to the second life were out of the scope of this study, it is interesting to highlight that although the cost increases together with the depth in the disassembly level, reaching a cell level disassembly will imply a higher recovery in materials. This recovery, apart from avoiding the extraction of new materials, can be interesting from an economic perspective as these can be introduced in a secondary market and therefore obtain additional economic incomes from their sell.

6.4 Conclusions

When the EV batteries have reached their end of life in the vehicle, they still have enough energy to be used in other applications as a Stationary Energy Storage Applications. Remanufacturing, repurposing and recycling are the three possible actions after that. In this study,one of the most important processes of the repurposing has been analysed in detail, that being the disassembly.

The Smart ForFour Li-ion battery was removed from the vehicle and disassembled, from battery level to cell level. For each operation, a registration of the required time, the required human resources were accounted for obtain the cost of each operation.

The disassembling process consists of at least two steps, removing the battery from car and the post-auto battery assessment. Disassembly battery to modules or disassembly module to cells will be also necessary in the case that a higher level of disassembly is required.

The operation with higher costs was the disassembly the battery to modules as it required 300 minutes and it costs 500 €. Although, the post-auto battery assessment had a similar cost, 442 €, while the time required is much bigger, 440 minutes, which means that process less steps and requires less manpower.

The depth of the level of the disassembly the battery determines directly the use of these in his second life considering that the reuse at module level increases the cost on 28 € and the reuse at cell on 44 € only seeing the disassembly process. Consequently, it can be stated that nowadays, only the repurposing of the whole battery would make sense in terms of economic profit. As it was highlighted by *Alfaro-Algaba et al.* the disassembly operation should end once the process reaches the disassembly state where the economic profitability is higher [84].

Remanufacturing at battery level has some advantages over either module or cell level such as a less time is required and a fewer cost. Therefore, the disassembling costs will play an important role in the repurposed battery selling prices. On the other hand, the reuse at module level presents interesting advantages such as the chance to design more versatile and scalable solutions, which could be more interesting despite their initial drawbacks for many second life applications.

Another important factor to be considered is that the cost of disassembling batteries due to the large battery configurations like the ones that nowadays can be found in the automotive industry which could make a significant change. Furthermore, the manufacturers efforts among standardizing the batteries that would lead to reaching economies of scale that would help to overcome current obstacles in the next years.

In order to calculate the total cost of repurposing, to the disassembling costs, it will be necessary to calculate the all costs to adapt the reuse batteries to the new application. At this point, this chapter leaves an open line of research for future work.

Chapter 7

Battery treatment centre

If you cannot explain something in simple terms, you do not understand it.

Richard Feynman.

7.1 Introduction

The growth in Electric Vehicle (EV) sales has led to Lithium-Ion batteries becoming an element indispensable within the automotive sector. Other means of transport such as scooters, motorcycles, trucks and electric buses also use these type of batteries.

The overall emissions of an EV are between 20% and 40% lower than those of Internal Combustion Engine Vehicles (ICEVs), with the current energy mix [115]. With the increase in green energy generation, the European Union (EU) expects by 2050, a reduction in emissions of up to 75% compared to those generated by powered vehicles for fossil fuels [116].

The benefits could not be better for the environment, but to ensure its true successful revolution, it is necessary to establish more efficient processes throughout the life of the electric vehicle, paying special attention to the Lithium-Ion battery.

Reusing batteries in energy storage applications or implementing more efficient recycling processes significantly improve the sustainability of batteries by reducing their environmental impact, while opening up new business possibilities with high economic potential.

EVs Lithium-ion batteries contain metals, rare earth elements and toxic and flammable materials that adversely affect the environment and could pose risk to human health [28]. Therefore, used EV batteries should be manipulated, disassembled and/or recycled at dedicated facilities prepared for such a purpose to do it in an efficiently and safely way [30], otherwise a huge number of discarded batteries end up in landfills without any recycling at all, contributing substantially to environmental pollution.

Moreover, the transportation of theses batteries to the repurposing and recycling facilities is a potential technical challenge as they are classified as hazardous waste which makes transport expensive and highly regulated [117].

In consequence, the aim of this chapter is to evaluate the economic feasibility of setting up used battery manipulating plant in Spain.

7.2 Current situation

Although Spain is still far from other northern European countries in terms of the penetration of electric cars, the fact is that more and more Spanish drivers are deciding to opt for electric mobility. The arrival of new models, some of which are more affordable, has given a real boost to the registration of this type of vehicle. Figure 7.1 presents the forecast for electric car sales in Spain from 2020 to 2030, differentiating the Battery Electric Vehicle (BEV) and Plug and Hybrid Electric Vehicle (PHEV). In addition, it is also shown when the batteries of these vehicles reach the end of their automotive life.

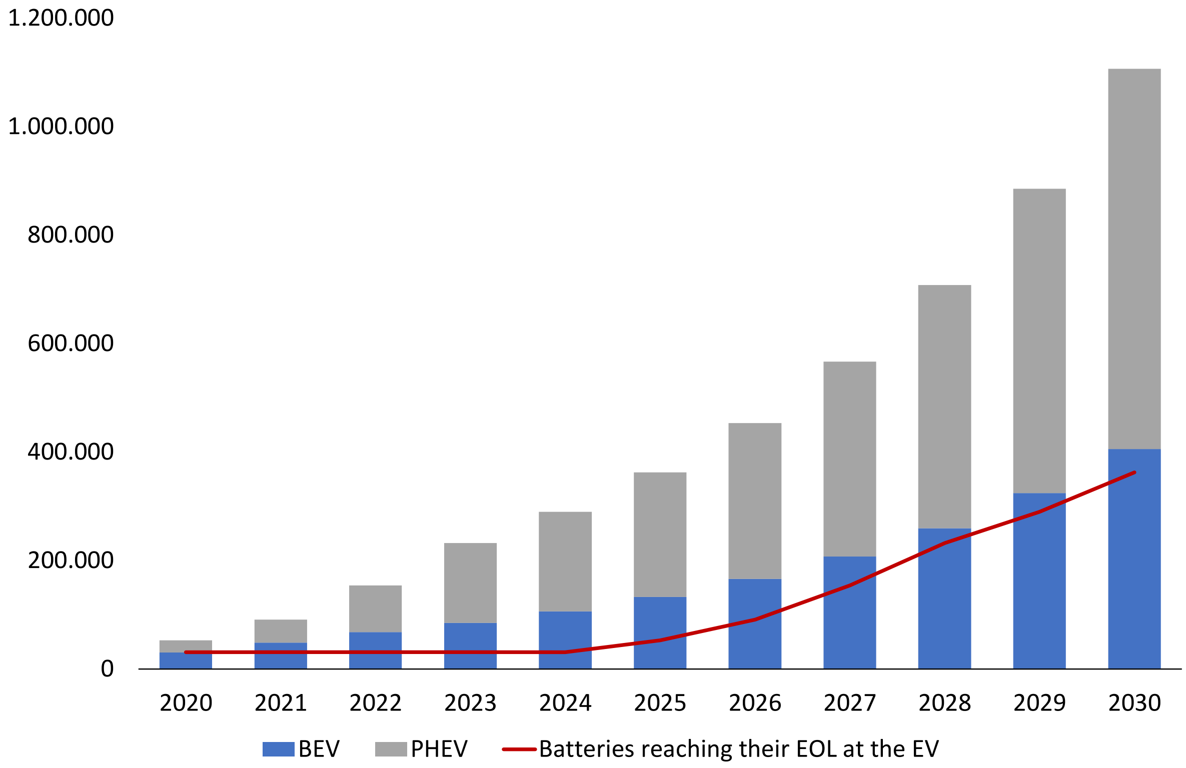


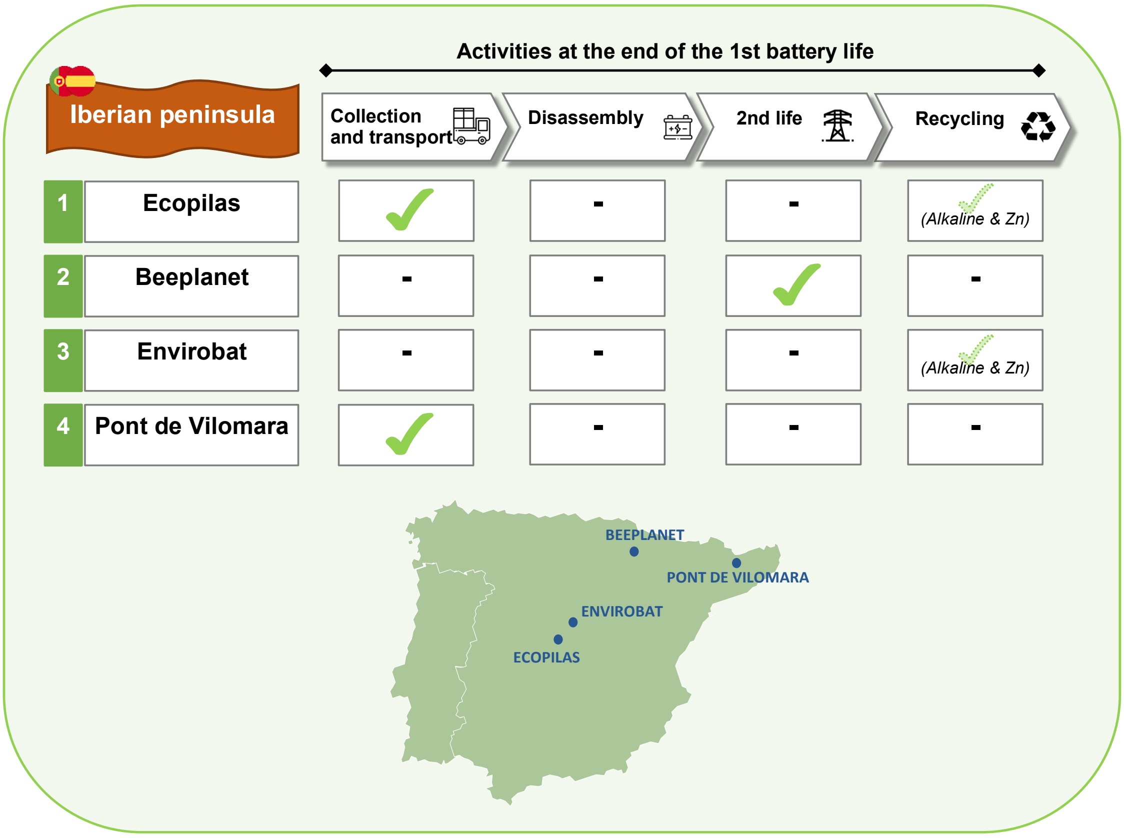
Figure 7.1: Sales of electrified vehicles in Spain [90]

Meanwhile, Spain is currently the 2nd largest producer of vehicles in Europe. Only a small part of this production is for electrified vehicles [90]. New investments for production and development of EV and batteries are mainly concentrated in Germany. This has also led to most battery recycling companies concentrating around these areas.

Therefore, it seems that there is an important disparity between the batteries that will reach the end of their automotive life in the next few years in Spain and the facilities prepared to handle, reuse and recycle these batteries. In consequence, this section analyses the facilities in Spain and Europe dedicated to these uses.

Four key activities have been identified once the battery has been removed from the vehicle: collection and transport, disassembly, recycling and 2nd life. Furthermore, an overview of which activities are best covered and where they are located is also detailed.

Figure 7.2 shows the companies in Spain currently working at some stage of the battery value chain from the moment the battery is no longer in the vehicle. At present it is important to highlight that only one company sells a Stationary Energy Storage System (SESS) with 2nd life batteries, as well as no company is yet involved in any battery disassembling process. In contrast, the the two companies involved in the logistics of Li-ion batteries, their mission is to transport these batteries to recycling centres located in France or Germany. Due to their large size and weight, the logistics costs of moving the batteries, as shown in the Table 5.3, are very high.



Activities at the end of the 1st battery life

Iberian peninsula		Collection and transport	Disassembly	2nd life	Recycling
1	Ecopilas	✓	-	-	✓ (Alkaline & Zn)
2	Beeplanet	-	-	✓	-
3	Envirobat	-	-	-	✓ (Alkaline & Zn)
4	Pont de Vilomara	✓	-	-	-

Figure 7.2: Activities at the end of 1st battery life in Spain

In contrast, as shown in figure 7.3, the scenario in the centre of Europe is vastly different because several companies that are working in any of the activities related to second life or battery recycling. Here, it is interesting to note the large number of existing recycling plants, where most of them also carry out the transport of the batteries and the dismantling.

It is also very important to take into account that batteries have to be shipped following certain guidelines, that is, packaged in rigid containers and in a manner to effectively prevent short circuits or violent rupture, allowing for the refurbishment facility to own and operate the vehicle used for transportation [114].

The collection can be performed in a local, regional or national level. However, it must be considered that if distances from collection points to the plants are too big, batteries will have to be stored before being collected which implies that the certified dismantling centres are required to have proper facilities for this purpose so the logistics and handling costs will be higher.

Activities at the end of the 1st battery life

	European Union	Collection and transport	Disassembly	2nd life	Recycling
1	Umicore	-	-	-	✓
2	Accurec	✓	✓	-	✓
3	Recupyl	-	-	-	✓
4	SNAM	✓	-	-	✓
5	Redux	✓	✓	-	✓
6	Dusenfeld	✓	✓	-	✓
7	Nickelhütte	✓	-	-	✓
8	STENA	-	-	✓	✓
9	POWERVAULT	-	-	✓	-
9	ADS-TEC	-	-	✓	-

Figure 7.3: Activities at the end of 1st battery life in Europe

Furthermore, batteries for reusing or recycling can be recovered from the certified dismantling centres where cars are disposed for dismantling. They can arrive here by multiple ways [79]:

- The owner can leave the car at the dealership that will later send the car to the treatment facility

- The owner can bring it directly to the certified dismantling centre
- Municipal services collect abandoned cars and bring them to the certified dismantling centres

Another option is that batteries are collected from official car workshops. Once they are at the certified dismantling centre, cars are dismantled, and their batteries are removed. It may also occur that cars cannot be dismantled at these facilities, so they have to be transported to a disassembly plant where they might be stored for a period of time before being disassembled [118].

The selection of the location is a decisive economic factor, especially with regard to the collection of batteries. The transport routes to the treatment facilities have to be kept as short as possible to avoid costly transport considering batteries are classified as dangerous goods and are subject to high safety requirements [119].

7.3 Results and discussion

This section compares, taking into consideration investment and logistics costs together with the income generated by recycling and second life, the advantages and disadvantages of remanufacturing batteries that have reached the end of their life in the vehicle in Spain or in Germany.

Following the described in Section 5.2, the first scenario contemplates the collection of theses batteries generated in Spain during the period 2020 - 2030 according to EV's total sales and remanufacturing them directly in Spain. However, the second scenario, as Spain does not have facilities prepared for the handling and recycling of electric car batteries, is to send these batteries by ADR transport to Germany. Furthermore, in the first scenario, the investment of setting up a battery remanufacturing factory is considered. In addition, the incomes that these batteries can generate by being reused as a SESS, or directly recycled, are also detailed.

Table 7.1, after applying the failures and degradation battery premises detailed in Table 5.4, shows all the batteries that have been considered in this case study. Firstly, we differentiate between batteries that are in a critical state and will therefore require special transport, and batteries that are in good condition. Secondly, a distinction is also made between BEV and PHEV batteries, since when calculating logistics costs, one truck can carry 4 BEV batteries or 4 PHEV batteries. It is important to note that all damaged batteries are transported on their own. Finally, the total number of batteries treated is detailed.

Table 7.1: Batteries treated during the period analysed

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
SAFE	1.933	3.528	6.239	10.374	15.667	22.704	31.980	44.151	46.804	51.742	59.793
UNSAFE	157	286	502	828	1.235	1.746	2.390	3.205	3.177	3.216	3.285
BEV	1.376	2.295	3.596	5.277	7.482	10.515	14.563	19.867	21.068	22.938	25.775
PHEV	715	1.519	3.144	5.926	9.420	13.934	19.807	27.489	28.913	32.019	37.303
TOTAL	2.091	3.814	6.740	11.203	16.902	24.449	34.370	47.356	49.981	54.957	63.078

Table 7.2 shows a summary of costs and revenues for 2020, 2025 and 2030. Figure 7.4 shows through a bar graph the logistics and the factory depreciation costs, in addition to the income

generated by second life and recycling for the first scenario. Furthermore, a line graph displays the accumulated result over the period analysed. On the other hand, Figure 7.5 shows in the same way the results for the second scenario. Only in Figure 7.4, factory depreciation costs are detailed, since it is considered that in scenario 2, the batteries will be transported to already existing plants in Germany.

The logistic costs for the scenario 1 are 699.317 € in 2020, 5.494.479 € in 2025 and 11.347.477 € in 2030. This implies a cost increase of 786% during the first five years, and 207% during the second five years. Furthermore, if the cost increase between 2020 and 2030 is compared, the digit escalates to 1.623%.

In contrast, the logistic costs for the scenario 2 are 1.233.462 € in 2020, 11.233.753 € in 2025 and 23.579.321 € in 2030. And obviously, the increases are greater than in the previous scenario. Between 2020 and 2025 the growth is 911%. Between 2025 and 2030 the increase is 210%. Considering the whole period, the inflation ascends to 1.912%.

In the scenario one, as far as the investment costs of the new factory in Spain are concerned, from 2020 to 2025, only one factory will be needed, so the accumulated cost during this period is 4 million euros. From 2026 to 2029, two factories will be needed, which will raise the cost of amortization of the investment to 5,3 million euros. The volume of batteries, will force to have a third factory in 2030, which implies a cost of 2 million euros. The total cost for the entire period analysed, 2020-2030, is 11,3 million euros.

On the income side, both second life and recycling have been considered. In this case, the results are the same for the two scenarios, since the values defined in the premises to determine the revenues are calculated in a generic way for the whole Europe.

Regarding the 2nd life incomes, 1.001.351 € in 2020, 13.144.521 € and 36.059.064 € in 2030, and as far as recycling is concerned the revenues are 195.515 € in 2020, 2.697.359 € and 10.232.306 € in 2030. The sum of these two revenues generates a total of 1.196.866 € in 2020, 15.841.880 € and 46.291.370 € in 2030.

Now, in order to understand the significance of logistics costs in the revenues generated, revenues minus logistics costs and investments (only in the first scenario) are detailed. Therefore, the real incomes in the scenario 1 would be -169.117 € in 2020, 9.680.734 € in 2025 and 32.943.893 € in 2030. Instead, in the scenario 2 would be -36.596 € in 2020, 4.608.127 € in 2025 and 22.712.049 € in 2030.

These results demonstrate the impact of logistics costs on the profits that can be generated by either of the two businesses envisaged with electric car batteries. Although in 2020 scenario 1 generates more losses than scenario 2, the first one starts one year earlier to generate profits. In 2025, both scenarios generate profits, although those generated in scenario 1 are 48% higher. In 2030, the benefits of scenario 1 are still greater, specifically 69%.

In addition, both Figure 7.4 and Figure 7.5 exhibit the accumulated total of the difference between revenues and costs over the whole period analysed. In scenario 1 there is a result of 139.525.074 €. Instead, in scenario 2, 84.588.720 €, which means that the benefits in scenario 1 are 165% higher. Comparing the two graphs, it can also be seen that in scenario 2 the break-even point is not reached until 2023, however, in scenario 1 from 2021 the balance is positive.

In addition to all the economic advantages described, scenario 1 has other advantages for Spain such as reducing CO_2 emissions by reducing transport. Figure 7.6 shows a comparison of the CO_2 emissions generated in each case. The emissions generated in each year are shown, as well as the accumulated emissions during the whole period. The accumulated emissions in the first scenario are 18 thousand tones of CO_2. Instead, in scenario 2, 71 thousand tones of CO_2. This means, therefore, that scenario 1 emits 53 thousand tones of CO_2 less, which results in a reduction of 74%.

Moreover, operating these businesses in Spain would have a direct impact on the country's economy with an increase in Gross Domestic Product (GDP) and the creation of new workplaces.

Table 7.2: Costs and incomes for the two scenarios analysed

Spain ⟶ Spain	**2020**	**2025**	**2030**
Logistic costs	- 699.317 €	- 5.494.479 €	- 11.347.477 €
Factory investment costs	- 666.667 €	- 666.667 €	- 2.000.000 €
2nd life	1.001.351 €	13.144.521 €	36.059.064 €
Recycling	195.515 €	2.697.359 €	10.232.307 €
Total	- 169.117 €	9.680.734 €	32.943.893 €
Accumulated	- 169.117 €	20.018.939 €	141.005.067 €
Number of factories	1	1	3

Spain ⟶ Germany	**2020**	**2025**	**2030**
Logistic costs	- 1.233.463 €	- 11.233.753 €	- 23.579.321 €
Factory investment costs	- €	- €	- €
2nd life	1.001.351 €	13.144.521 €	36.059.064 €
Recycling	195.515 €	2.697.359 €	10.232.307 €
Total	- 36.596 €	4.608.127 €	22.712.049 €
Accumulated	- 36.596 €	8.204.737 €	84.592.348 €

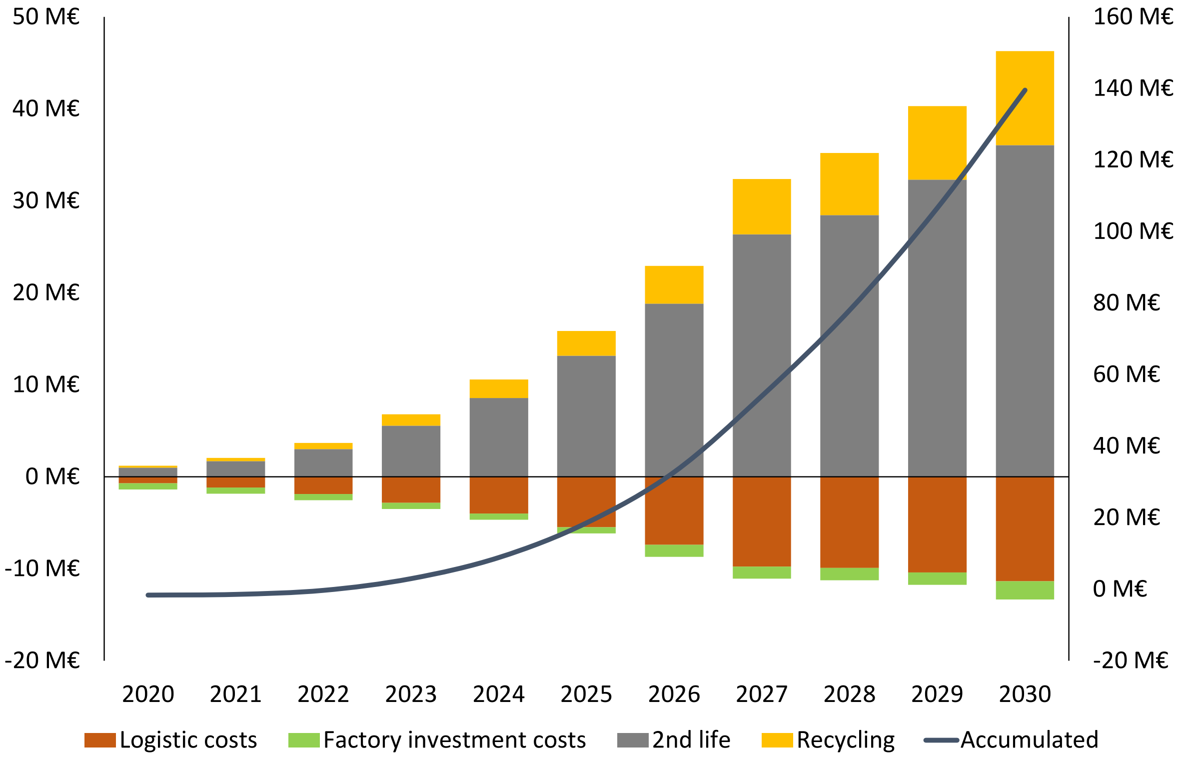


Figure 7.4: Costs and incomes. Scenario: Spain ⟶ Spain

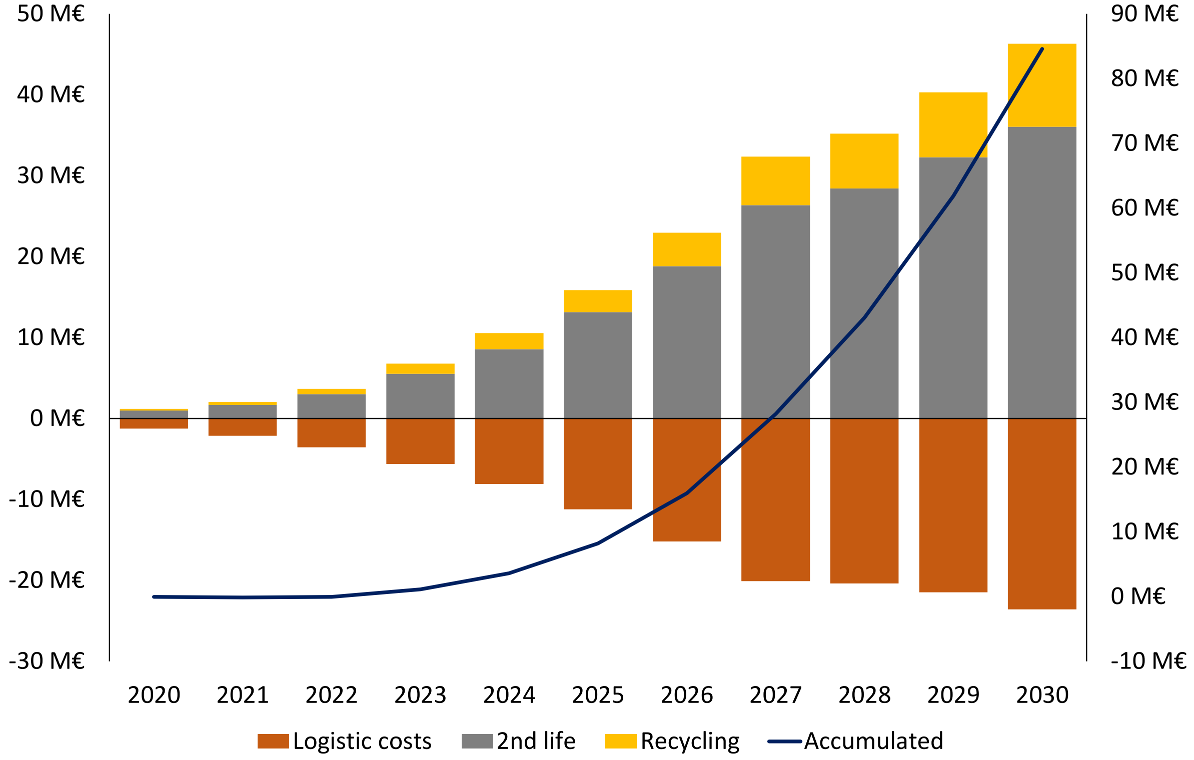


Figure 7.5: Costs and incomes. Scenario: Spain ⟶ Germany

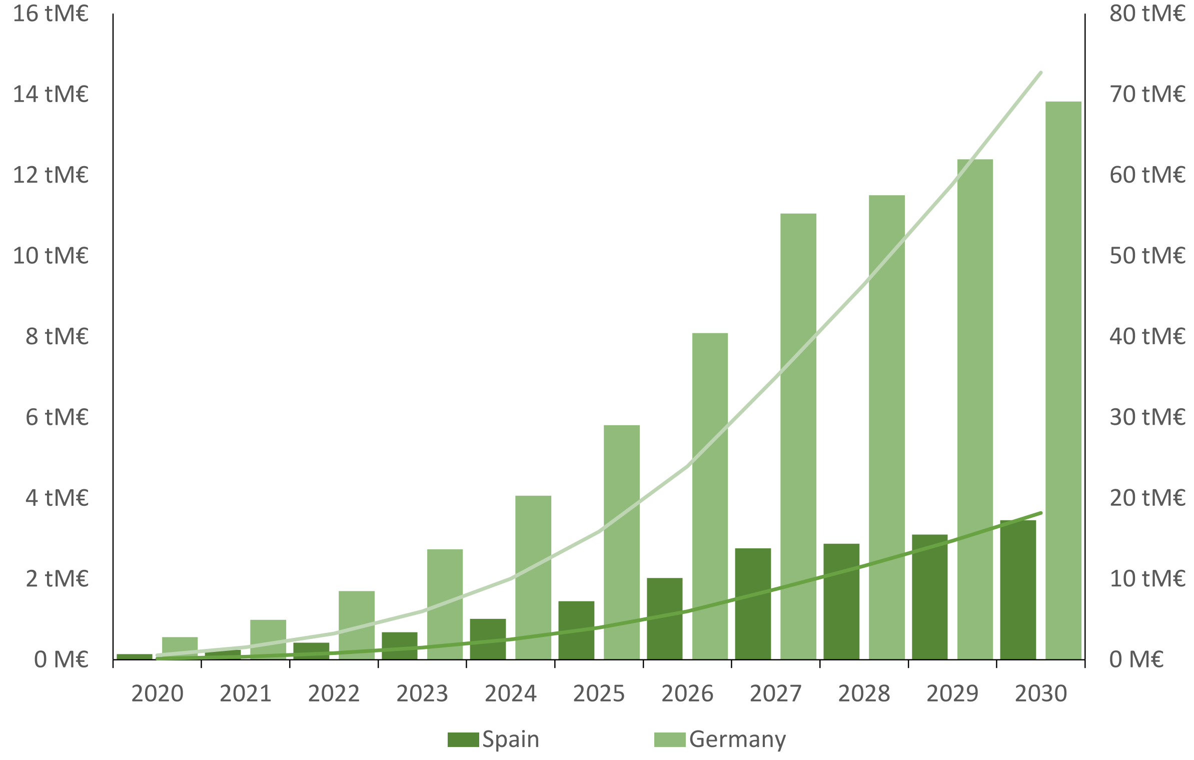


Figure 7.6: CO_2 emissions in both scenarios

7.4 Conclusions

This chapter assesses whether it is more economically viable to handle and prepare the batteries for second life or recycling once they have reached the end of their life in the vehicle in Spain than transport them to Germany to be treated there.

This study combines the knowledge of the logistics sector and the business around the EV battery. From this investigation, the huge incidence that the specialized transport of EV batteries has in the new businesses around it. In the scenarios studied, the logistical costs of transporting the batteries to Germany compared to local transport in Spain are on average 200% higher during the period 2020 to 2030. Moreover, it can be determined that in scenario 1, the investment in setting up a new factory only accounts for 15% of total costs. This determines that logistics costs play a more important role in determining the viability of building a new factory in Spain.

In addition, the specialised centres and processes in the treatment of batteries are identified and located on the map. In consequence, the concentration of these centres in the centre of Europe leads to high logistical costs to the countries furthest away from such centres.

It is important to highlight that the economic revenues obtained are extremely big, the fact that the total EV sales in Spain have been considered during the whole period from 2020 to 2030. This shows, that possibly more than one battery treatment factory in Spain will be needed in the coming years.

In addition to all the economic advantages described, scenario 1 has other advantages for Spain such as reducing CO_2 emissions by reducing transport. Moreover, operating these businesses in Spain would have a direct impact on the country's economy with an increase in GDP and the creation of new workplaces.

Chapter 8

Economic model for 2nd life batteries

> The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge.
>
> Stephen Hawking.

8.1 Introduction

In the last few years, 2nd life batteries have become the focus of research interest due to their countless benefits from an economic and environmental point of view. In addition, both Original Equipment Manufacturers (OEMs) and energy sector companies have launched numerous projects to demonstrate the feasibility of reusing these batteries [120]. The main objective of most of these projects is to ascertain both technical and economic feasibility in order to develop new businesses around second life batteries.

The first objective, which is technical, has already been demonstrated relatively easily in many of these projects. But in contrast, problems arise to determine the economic viability of installing a Stationary Energy Storage System (SESS) using second life batteries due to one of the fundamental restrictions of this technology residing in the ageing of the battery. The consequences of battery ageing restrict its performance and take place throughout its entire life, whether the battery is used or not, which is a significant disadvantage in real usage. Therefore, ageing becomes a crucial factor in determining the return on investment of any installation with a SESS. In addition, another disadvantage of the ageing phenomena is that it requires a lot of testing time in order to reach useful conclusions [121]. Therefore, simulation becomes a very powerful tool to save money and time or to avoid unnecessary dangerous tests.

Consequently, one of the solutions proposed in this chapter is the development of a mathematical simulation model capable of determining both the ageing of the batteries of a SESS and the savings that they can generate in order to determine whether or not its installation is viable.

8.2 Process of calculating the feasibility of installing a SESS

This section details the process of calculating the feasibility of installing a SESS using 2nd life batteries taking into account the battery ageing and the economic profit.

The calculation process is divided, as shown in Figure 8.1, in twelve points. The economic model, which evaluates the greatest economic savings in terms of electricity bill and determines the size of the SESS in order to maximize the profit is detailed from point 1 to point 9. The ageing model is executed at step 10 of the process.

1 **Select the case study and run the economic model**
The first step in the process is to select the case study to analyse.

2 **Calculate the real electricity bill without SESS**
This point calculates the economic cost of electricity consumption for each of the scenarios during the year under analysis according to the law of the Spanish electric sector [122] and the *"Real Decreto 1164/2001"* [101] where access tariffs to the electricity distribution networks are established.

Appendix.D shows the MATLAB script used at this point to calculate the real electricity bill without SESS.

3 **Calculate SESS power & capacity**
In this section, the most important SESS parameters that fit the case study are calculated. This action is repeated until the parameters that contribute to a better use of the SESS and greater profits are found. It is important to dimension the SESS well in order to obtain the largest possible savings.

It should be noted that both, upper and lower SOC margins, have been left in the batteries for safety reasons. The upper limit is set at 95% and the lower limit at 10% of SOC. These limits mean that the available capacity in each battery is reduced, and thus a higher number of batteries is needed.

Additionally, the capacity in the economic model will be calculated considering that the SESS must be able to work until batteries reach the end of their second life. This means that the SESS capacity must be oversized considering the battery ageing.

Considering that the share of PHEV sales is higher than that of BEV, and this is expected to be maintained according to *Sitjabat et al.* at least until 2023 [123], this model will use these type of batteries in the simulation. Therefore, within approximately 8 years once these batteries have reached their end of life in the car, larger volumes of PHEV batteries will be available for use as SESS.

Appendix.F shows the MATLAB script used at this point.

4 **Estimate new electricity contract parameters and simulate electricity bill cost with SESS**
The installation of a SESS causes the modification of the parameters of electrical contracting to reduce its cost. In this section, the new parameters of the power term are calculated. Electricity bill cost is simulated using strategy 1 and 2.

- **Strategy 1: ENERGY ARBITRAGE**
  The battery is charged during the cheapest period of the day. The battery is dis-

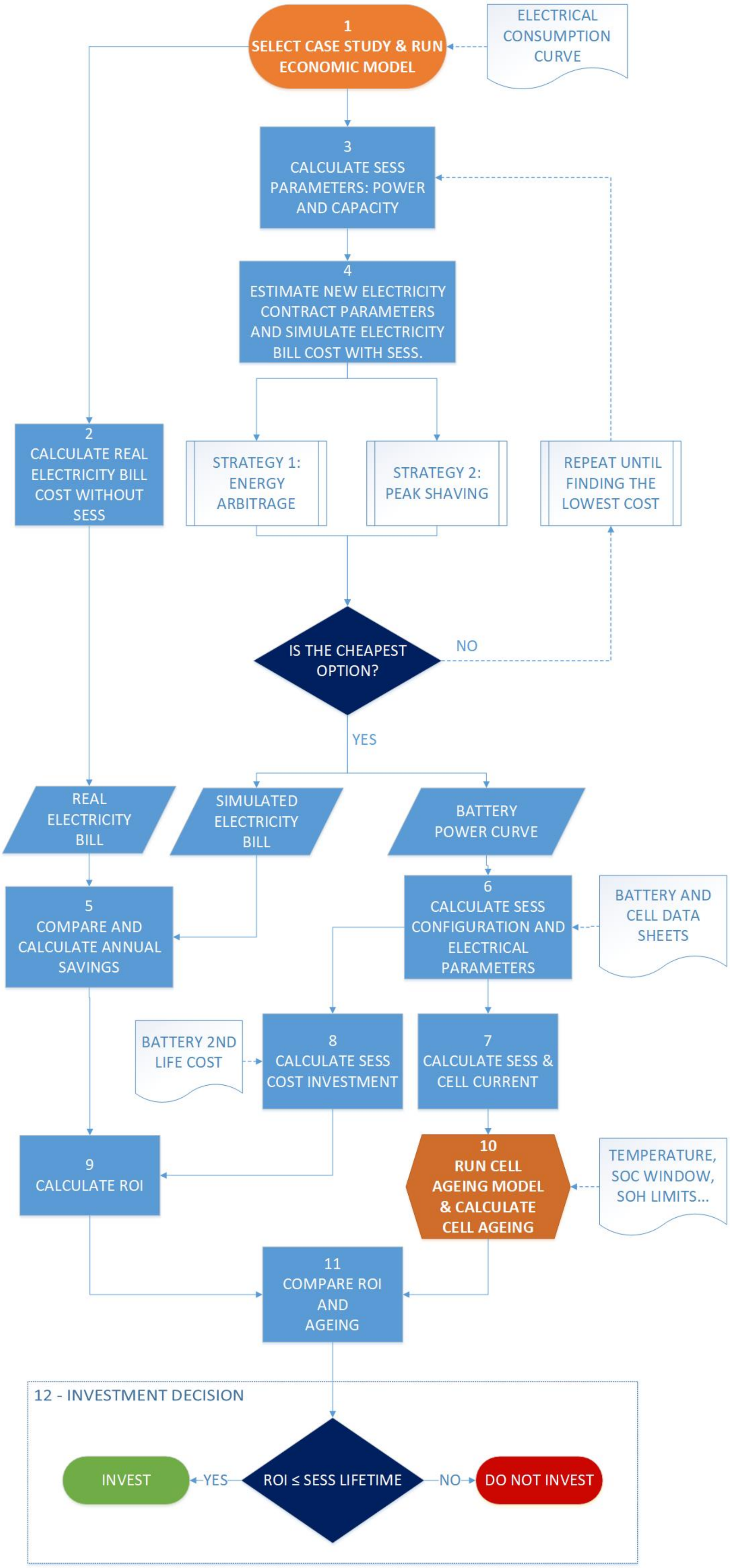


Figure 8.1: Calculation process

charged during the most expensive period of the day. Loading / unloading is only carried out if possible.

- **Strategy 2: PEAK SHAVING**
  The battery is charged during the cheapest period of the day. The battery is discharged when there is excess power demand of the contracted power.

The economic model always prioritizes the use of the energy available in the battery when the economic profit margin is higher. The battery charge and discharge decision are made based on two system variables: battery status and time varying electricity price. Therefore, the main objective of the model is to find a daily strategy between charging and discharging where profits are maximized [124]. Consequently, the charging and discharging strategy is even more fundamental point for second life batteries to provide a beneficial business case [125].
At this point, the power curve with which the SESS will work under the conditions set throughout the whole year of study is obtained.

Appendix.D shows the MATLAB script used at this point to calculate the simulated electricity bill with a SESS. Appendix.H shows the MATLAB script used for Energy Arbitrage strategy and Appendix.I for Peak Shaving .

5 **Compare and calculate annual savings**
This section compares the real cost of each scenario with the best of the simulated results and calculates the possible annual savings that the installation of a SESS would entail by the equation 8.1.

$$Savings \quad = \quad Real\ cost - Simulated\ low\ cost = [€] \tag{8.1}$$

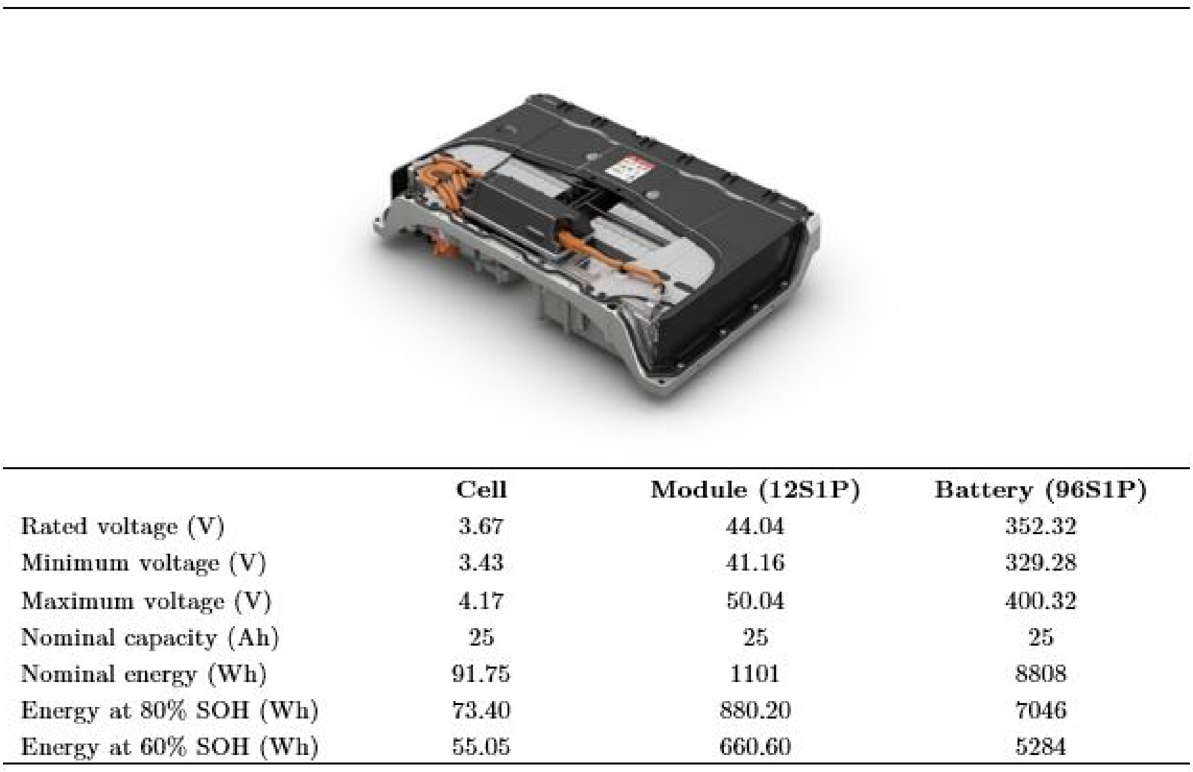
6 **Calculate SESS configuration and electrical parameters**
The SESS is built with the connection of several batteries in series and in parallel which will determine the voltage and total capacity of the SESS. Figure 8.2 shows the rated, minimum and maximum voltage, the nominal capacity and the energy, at cell, module and full battery level of the batteries used in this study.

According to the results of point 3, the SESS configuration taking into account the battery of the Golf GTE (see Figure 8.2) is calculated using equations 8.2 and 8.3. By means of the battery data sheet that is intended to be used and the cell data sheet, it is determined how many batteries must be connected in series and in parallel to obtain the capacity.

$$SESS_{voltage} = Cell_{voltage} \times n\ batteries\ series = [V] \tag{8.2}$$

$$SESS_{capacity} = Cell_{capacity} \times n\ batteries\ parallel = [Ah] \tag{8.3}$$

7 **Calculate CELL current**
At this point, the current that passes through each of the battery cells is calculated. First, using the power curve profile of the battery calculated in point 4, the SESS current is determined. Afterwards, as in the Golf GTE battery cells all are in series, the total SESS current is divided by the number of batteries in parallel in the SESS to get the current in each cell (Volkswagen, 2019).



	Cell	Module (12S1P)	Battery (96S1P)
Rated voltage (V)	3.67	44.04	352.32
Minimum voltage (V)	3.43	41.16	329.28
Maximum voltage (V)	4.17	50.04	400.32
Nominal capacity (Ah)	25	25	25
Nominal energy (Wh)	91.75	1101	8808
Energy at 80% SOH (Wh)	73.40	880.20	7046
Energy at 60% SOH (Wh)	55.05	660.60	5284

Figure 8.2: Battery of the Volkswagen Golf GTE 1st generation [126]

$$SESS_{current}(i) = \frac{Battery_{power}}{SESS_{voltage}} = [A] \tag{8.4}$$

$$Cell_{current}(i) = \frac{SESS_{current}}{n\ batteries\ parallel} = [A] \tag{8.5}$$

8 **Calculate SESS cost investment**

At this point the total cost of purchasing a SESS is calculated by considering the battery 2nd life cost, the inverter cost, the material cost and the labour cost. Other elements such as operating and maintenance costs, replacement costs, end-of-life costs and financial costs are outside the scope of the study.

Estimating the purchase price of second life batteries is one of the most delicate points of this study, as it is a product not yet available in the market and there are many price variations in the literature consulted, the results can change considerably [5]. *Ansean et al.* considered that the cost for these batteries should not exceed 100 €/kWh [127]. Further on, *Elkind* says that Electric Vehicle (EV) owners should expect between 20€/kWh and 100€/kWh for selling its used battery [128] and *Neubauer et al.* forecasted the cost of 2nd life batteries between 38€/kWh and 132€/kWh [57]. Nonetheless, all authors agree on the fact that the cost of the reused batteries should be lower than 50% of the new ones [129]. Taking all of this into account, the price of the battery in this study is estimated at 50€/kWh when it reaches an 80% of SOH. Furthermore, Table 8.1 shows other considered costs in the study, such as the cost of the installation of power electronics and equipment (specific cost per power), costs of electric material and labour costs, according to *Diaz González et al.* [42].

Table 8.1: SESS investment costs per unit

Specific cost per storage	50 €/kWh
Specific cost per power	80 €/kW
Specific cost of material	30 €/kW
Specific cost per labour	30 €/kW

Using equations 8.6, 8.7, 8.8 and 8.9 the cost of each component of the SESS cost are calculated for later solving equation 8.10 find the total cost.

$$\mathrm{B2LC} = \mathrm{SESS}\ Capacity[kWh] \times Specific\ cost\ per\ storage[€/kWh] = [€] \tag{8.6}$$

$$\mathrm{IC} = \mathrm{SESS}\ Power[kW] \times Specific\ cost\ per\ power[€/kW] = [€] \tag{8.7}$$

$$\mathrm{MC} = \mathrm{SESS}\ Power[kW] \times Specific\ cost\ per\ material[€/kW] = [€] \tag{8.8}$$

$$\mathrm{LC} = \mathrm{SESS}\ Power[kW] \times Specific\ cost\ per\ labour[€/kW] = [€] \tag{8.9}$$

$$\mathrm{SESS}\ Cost\ Investment = \mathrm{B2LC} + \mathrm{IC} + \mathrm{MC} + \mathrm{LC} = [€] \tag{8.10}$$

9 Calculate Return of Investment (ROI)

The last step of the economic model, solving equation 8.11, is to calculate the return on investment considering the necessary investment and the savings that the installation of the SESS produces annually in each of the scenarios.

$$\mathrm{ROI} = \frac{\mathrm{SESS}\ Cost\ Investment}{Savings} = [Years] \tag{8.11}$$

10 Run Cell ageing model & calculate cell ageing

Once all the economic parameters have been calculated, at this point, the ageing model is applied to determine the lifetime of the SESS.

The working conditions of the cell ageing model are set as able 8.2 shows. First, the SOC limits follow the battery working parameters established by Volkswagen [126]. Then, temperature has been set at 23ºC (room temperature) due to the fact that the Association of the German Automotive Industry recommends in the test specification for Li-ion battery systems for hybrid electric vehicles that this is the best temperature to slow down the ageing phenomena of the batteries [130] and when lesser lithium depletion occurs [131]. In the studied scenarios the temperature can always be kept relatively constant since the SESS remains in a controlled air-conditioned room. Finally, there has been consideration for the end of the lifetime of the batteries in their second life in 60% SOH because it cannot be assured that there will not be a dramatic change in the ageing behaviour from this point onwards [72][132]. Straightaway, the cell current calculated in the point 7 is introduced as the main input. The ageing model calculates the cell lifetime under the conditions described.

Table 8.2: Cell ageing model-working parameters

State of Charge (SOC)	Lower security limit	0,10
	Upper security limit	0,95
State of Health (SOH)	Lower security limit	0,10
	Upper security limit	0,95
Temperature		23ºC

11 Compare ROI and ageing
This section compares the results obtained by both the economic model in terms of the ROI of the investment and the battery-ageing model in terms of the lifetime of the SESS.

12 Investment decision
This last step decides if the investment in the installation of a SESS is economically viable. If ROI is smaller than the SESS lifetime, the investment is feasible. In contrast, if ROI is bigger or equal than the SESS lifetime, the investment is not feasible.

8.3 Conclusions

This chapter explains step by step the process of calculating the viability of installing a SESS using 2nd life batteries. It also explains how the battery ageing model previously developed by the Universitat Politècnica de Catalunya – BarcelonaTech (UPC) has updated, including the economic study of installing a SESS.

The economic feasibility of using batteries to store energy is greatly determined by the battery's price and lifespan. Although, the utilization of 2nd life batteries has decreased in the first term, it is essential to jointly analyse the Return of Investment (ROI) of installing a SESS and the ageing of those batteries.

Chapter 9

Validation of the economic model

The significant problems we have cannot be solved at the same level of thinking with which we created them.

Albert Einstein.

9.1 Introduction

Electric Vehicles (EVs) are considered a viable alternative to Internal Combustion Engine Vehicles (ICEVs) and as a result of recent advances in battery technologies, sales are increasing year on year. However, recycling these batteries at the end of their useful life in the car can be a problem because they contain materials that can harm human health and the environment. Thus, car manufacturers believe that when those batteries have finished their first life in an EV, they still contain enough energy and capacity to be used in a Stationary Energy Storage Systems (SESSs), significantly contributing towards an increased sustainable transport sector in the future.

This chapter focuses its analysis on the viability of a SESS installation, considering battery ageing from an economic perspective in two different real scenarios in Spain. This study simulates the electricity bill cost with and without SESS and calculates the annual savings accordingly. Following, the Return of Investment (ROI) of installing a SESS is calculated. Afterwards the lifetime of the batteries is calculated in order to compare it with the ROI and to decide if the installation of a SESS is advisable from an economic point of view.

Major results indicate that any feasibility study of installing a SESS must be studied from an economic and battery ageing point of view.

9.2 Case studies analysed

In Chapter 8 the reader could observe the importance and relevance of having an accurate model capable of simultaneously calculating the ageing and economic viability of a SESS. Accordingly, this section describes two real cases that will help to validate the economic model. The battery ageing model was previously validated together with Audi in the project: *Batteries Second Life (BSL)* [133].

The first case corresponds to a furniture factory located in “La Sénia” (Tarragona) with an electrical contract at tariff 3.0A and with a maximum contracted power of 80kW. Figure 9.1 shows the yearly demand of power for the case study 1. It can be observed that there are many spaces of time where the electrical demand is almost at zero. The three major times correspond to Easter, summer and Christmas holidays respectively. All the other low consumption valleys, the smaller, correspond to weekends, since the company only works from Monday to Friday. It can also be observed that the maximum power demand changes daily because of the variability of the plant production.

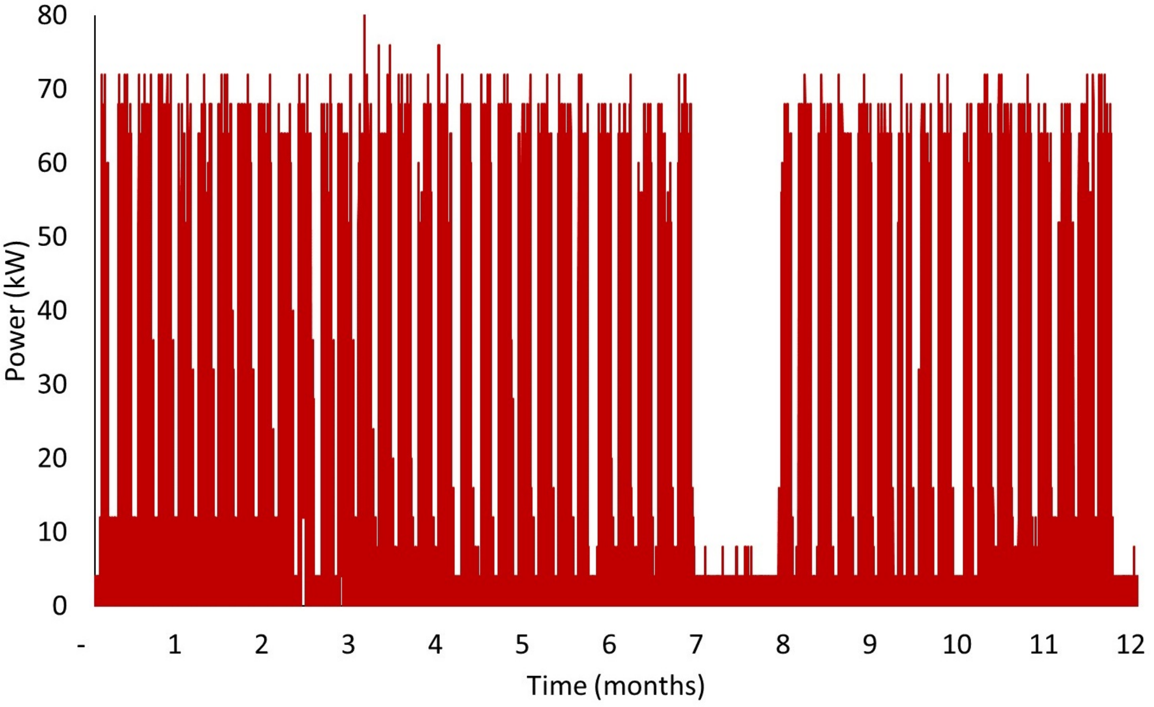


Figure 9.1: Power yearly demand for the case study 1

In contrast, the second case corresponds to a hotel located in Santa Cruz de Tenerife (Canary Islands) with an electrical contract at tariff 6.1A and with a maximum contracted power of 490kW. Figure 9.2 shows the power yearly demand for the case study 2. In this case there are no times of null consumption because the hotel is open 24 hours every day of the year. It is important to notice that electricity consumption varies throughout the year in the range of 100 to 600 kW showing a slight increase in winter.

Given that the behaviour in both cases is very similar during work-days for scenario 1 (Figure 9.1) and for the whole week in scenario 2 (Figure 9.2), a randomly chosen day is taken as example (Figure 9.3) of the daily electricity consumption for scenarios 1 and 2. Note the increase in the consumption from 7 to 16 h in the scenario 1, while the consumption in scenario 2 increases when the sun rises and decreases after 22 h in the night.

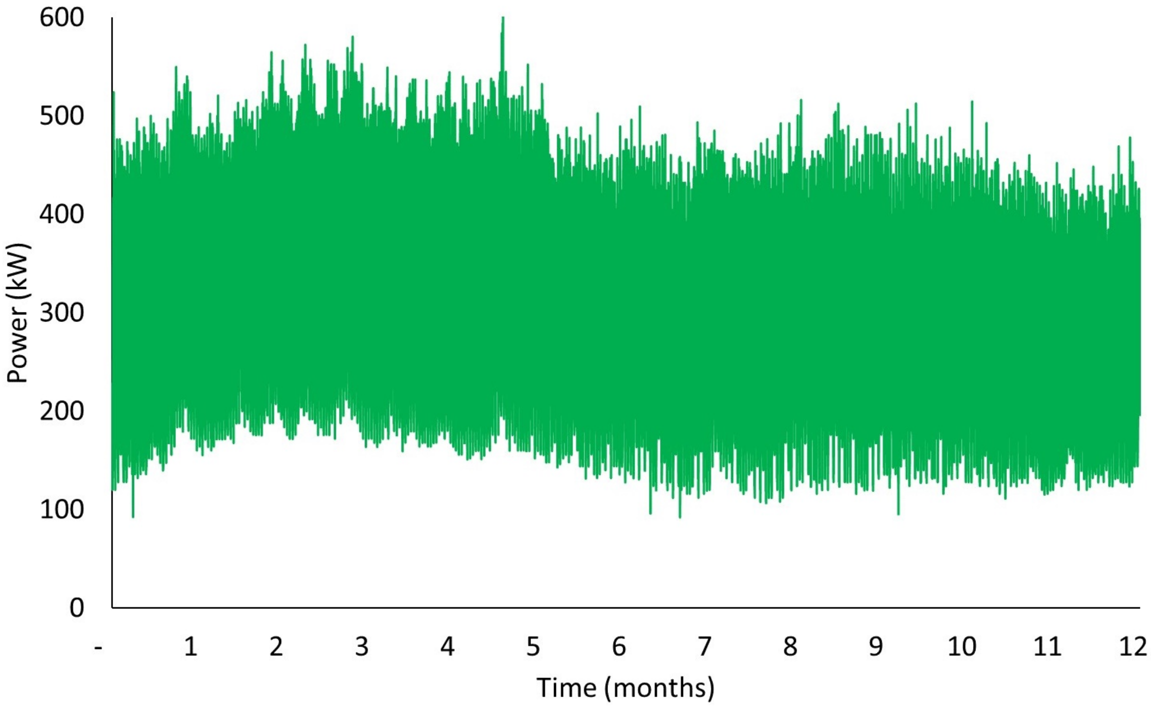


Figure 9.2: Power yearly demand for the case study 2

Figure 9.3: Typical power daily demand for the case of study 1 & 2

Note that this study is based on the registers of a complete year. These registers have been obtained directly from the electric meter of each installation under study during the year 2018.

These power profiles of each scenario are introduced in the economic model developed in Chapter 8. The economic model, programmed using MATLAB, calculates the electricity bill in each case, with and without SESS. In addition, the size of the SESS is optimised in order to reduce investment and maximise savings. All this, together with the SESS ageing study using the power curve in one year of each case.

Table 9.1 shows the electricity prices (€/kWh) that have been used in the simulation for both case studies, each one with the corresponding access tariff. These prices correspond to the average prices during 2019 of the five electrical companies with the highest turnover in the same year. Each of the periods indicated in Table 9.1 correspond to the different schedules according to each electric tariff as determined by the electricity regulations. AppendixG shows the MATLAB script used to introduce the electricity prices.

Table 9.1: Electricity price [€/ kWh]

	TARIFF 3.0A	**TARIFF 6.1A**
Period 1	0,111200	0,101173
Period 2	0,090727	0,089755
Period 3	0,066407	0,079262
Period 4		0,072770
Period 5		0,069834
Period 6		0,060671

9.3 Results and discussion

This section presents step by step the results following the same order the process of calculating the feasibility of installing an SESS described in Chapter 8 in Section 8.2.

The first result obtained, as shown in Table 9.2, is the cost of the electricity bill in each scenario for one year. In the real case, the contracted power in the scenario 1 is 80 kW with a cost of 24.896 € during the year 2018, in contrast, for the same period, the contracted power in the scenario 2 is 490 kW with a cost of 328.968 €.

Table 9.2: Electricity bill cost without SESS

Without storage	**Case study 1**	**Case study 2**
Contracted power [kW]	80 kW	490 kW
Cost [€]	24.896 €	328.968 €

The following step is to calculate the main SESS characteristics. The main objective is to find the capacity and power that best suit each case. As Table 9.3 shows, SESS capacity in scenario 1 is 200kWh and its power is 40kW. In the scenario 2, the capacity is 5000 kWh and the power is 100kW. These values were calculated by the economic model with the aim of achieving the greatest possible savings in each case.

Table 9.3: SESS characteristics by case of study

	Case study 1	**Case study 2**
Capacity [kWh]	200 kWh	5.000 kWh
Power [kW]	40 kW	100 kW

Once the main parameters of each SESS have been calculated for each scenario, Table 9.4 shows the simulation results of the electricity bill taking into account the two selected strategies (energy arbitrage & peak shaving) together with the contracted power that entail the greatest savings. Marked in green are the results of each scenario with a lower cost.

Figure 9.4 and Figure 9.5 compare graphically both strategies in each case study and show which are the tipping points where trends change, resulting in lower cost. It is interesting to note that in both study cases, the greatest savings were found following the energy arbitrage

Table 9.4: Simulated electricity bill using the two strategies for the cases of study

	Contracted power	Energy arbitrage	Peak shaving
Case study 1	80 kW	23,47 €	24,91 €
	70 kW	23,04 €	24,70 €
	60 kW	**22,97 €**	23,75 €
	50 kW	23,08 €	24,45 €
Case study 2	490 kW	310,41 €	325,92 €
	450 kW	307,47 €	319,89 €
	400 kW	**306,60 €**	313,51 €
	350 kW	309,01 €	315,42 €

strategy. This occurs since peak shaving has the sole purpose of cutting the power peaks when they exceed the contracted power. On the other hand, energy arbitrage, as explained above, aims to charge the batteries at times when the energy is cheaper, to use it when it is more expensive. However, what happens because of this strategy, is that the power peaks in the most expensive periods are also reduced since the electrical consumptions have moved towards the cheapest periods. Therefore, the energy arbitrage strategy indirectly could also be said to be doing the peak shaving strategy for the case of analysis.

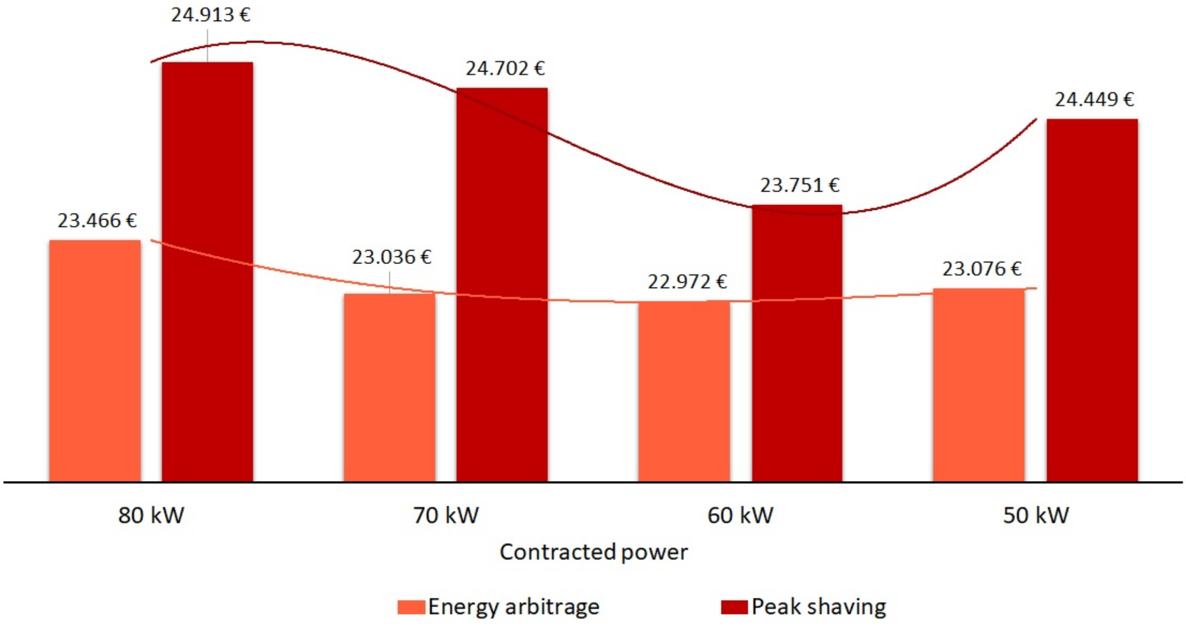


Figure 9.4: Comparison of the simulated cost according to the strategy used in case study 1

The next step is to calculate the configuration and parameters of the SESS in each case of study taking into account the battery parameters, as shown in Figure 8.2 in Chapter 8, and the SESS requirements in terms of capacity and power calculated before as presented in Table 9.3. Table 9.5 shows the final configuration of the SESS for each case of study. The calculations have been made using equations 8.2 and 8.3 of the calculation process. In both cases, the capacity of the SESS has been calculated on the premise that the SESS must be able to offer the capacity determined by the economic model until the end of its useful life. Safety margins have also been considered. Consequently, 46 and 1.116 batteries are needed to reach the SESS requirements in the case study 1 and 2 respectively. Only two strings in series are needed in each case to reach

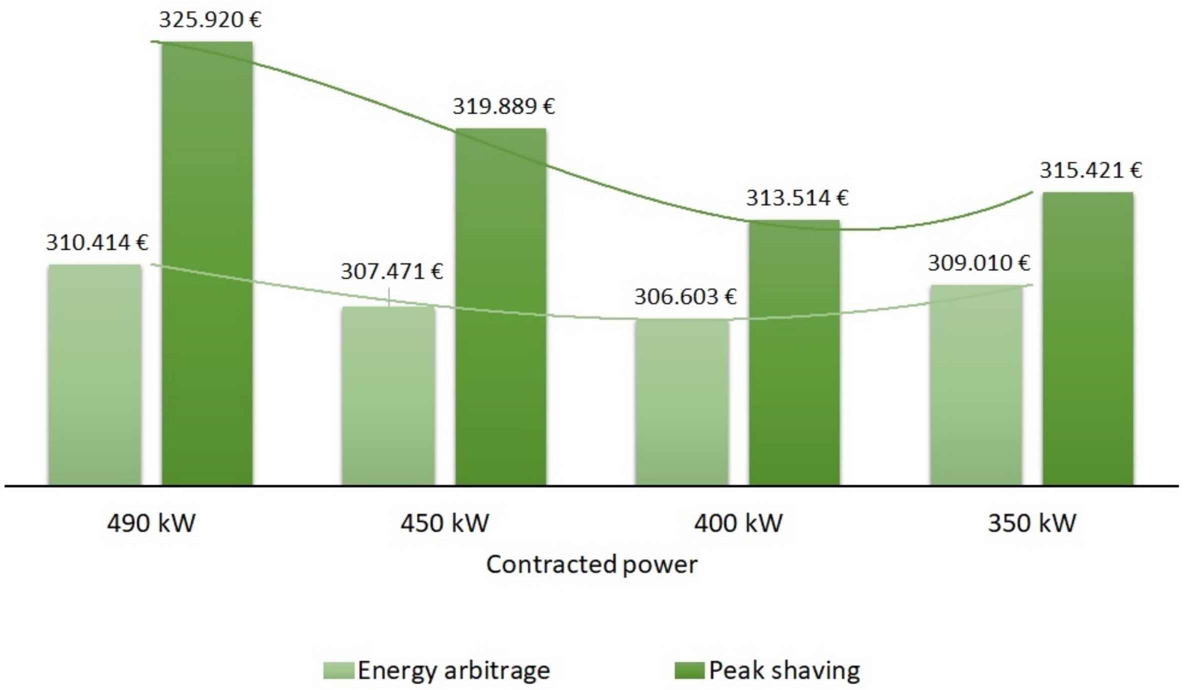


Figure 9.5: Comparison of the simulated cost according to the strategy used in case study 2

the first possible voltage value greater than 400 V due to this is the voltage value of the electrical network in Spain.

Table 9.5: SESS configuration and electrical parameters by case of study

SESS configuration	**Case study 1**	**Case study 2**
Number of batteries strings in series	2	2
Number of batteries in parallel	23	558
SESS voltage [V]	704,64	704,64
SESS capacity [Ah]	1.125	13.950
SESS energy content [kWh] (new)	405,17	9.829,73
SESS energy content [kWh] (2nd life – 80% State of Health (SOH))	324,13	7.863,78
SESS energy content [kWh] (2nd life – 60% SOH)	243,10	5.897,84
SESS useful energy [kWh] with State of Charge (SOC) working limits 15%	206,64	5.013,16

Using equation 8.1, the savings that the installation of the SESS produces each year are calculated. The total cost of the investment is calculated using equation 8.10. Finally, one of the two most important values, ROI, can now be calculated. Equation 8.11 allows us to evaluate the return of investment for each case study. For the case of study 1, as it can be seen in Table 9.6, the ROI is 8,42 years, while for the second, it is 17,58 years.

Once the economic model has calculated all the necessary parameters, the study proceeds to calculate the ageing of the SESS to determine if the investment is profitable. Using equation 8.4 and 8.5 the cell current for each case is calculated as Figure 9.6 shows. It can be clearly observed, in the two cases, that the battery absorbs energy from the grid during the early morning, when the price of energy is cheaper, to use it later in the moments where it is more expensive. Figure 9.6 also shows that the C-rate either during the charge and discharge in both cases is lower than

Table 9.6: Savings, investment & ROI by case of study

	Savings / year	**SESS cost investment**	**ROI**
Case study 1	1.924 €/year	21.806,50 €	11,33 years
Case study 2	22.365 €/year	407.189,00 €	18,21 years

0,12C (or C/8). These low current intensities mean that the temperature increase caused by the joule effect on these batteries can be considered negligible.

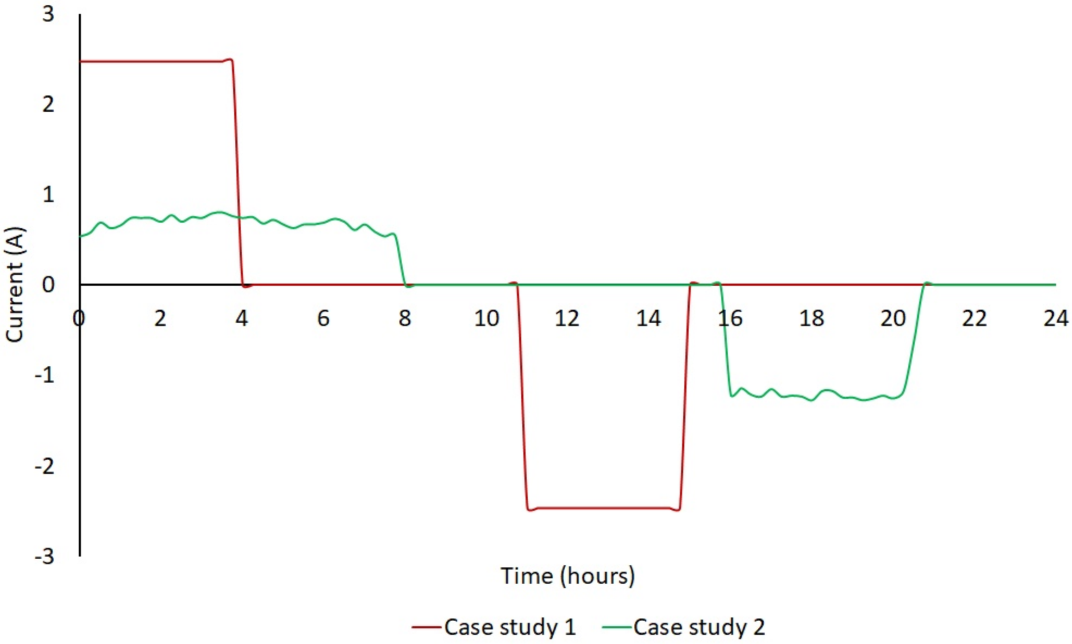


Figure 9.6: Cell current on a typical day. Case study 1 & case study 2

Finally, the current profile that will pass through each cell will be introduced in the ageing model. Figure 9.7 shows the capacity fade of each cell depending on the current above calculated. The simulation in both cases starts at 80% of SOH and ends at 60% getting 12,44 and 13,07 years of useful life in each case. It has been shown that the ageing of the SESS is very similar since in both cases the current that passes through the cells is less than 3 amperes, which means a C-rate of 0.12 when these batteries are used to working in currents up to 10C [134]. Another interesting point to emphasize is that the ageing of the batteries in both cases is practically lineal. This is justified because the stationary applications are assumed to have a less demanding cycling pattern and does not include degrading factors such as regenerative braking [26].

With all the calculations and simulations performed, it is time to determine the economic viability of the SESS installation. As it can be observed in Table 9.7, in case of study 1, the ROI is smaller than the cell ageing, in fact 10% less, which means that for a little more than one year the SESS in this case will be generating economic benefits. On the other hand, the results in the case study 2 are quite the opposite, with the ROI 40% bigger than the cell ageing making the investment not economically profitable in any case.

In case study 2, the capacity of the SESS is 25 times larger than in case study 1, and consequently, the investment as well. This is clearly the reason why the investment is in no way advisable. Although battery prices have dropped a lot in recent years, this is not enough to make the SESS installation attractive [135]. Furthermore, in case study 1, although the ROI is

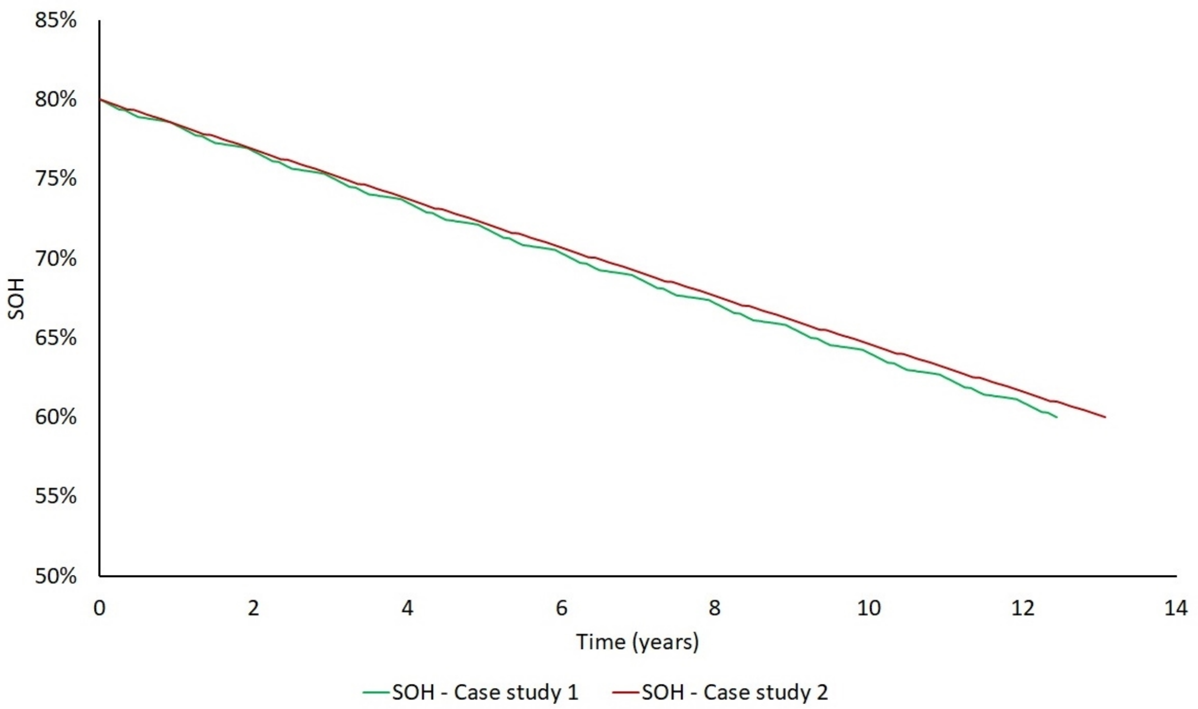


Figure 9.7: Cell capacity fade for case study 1 & case study 2.

Table 9.7: ROI and Cell ageing comparison by case of study

	ROI	**Cell ageing**	**Investment**
Case study 1	11,33 years	12,5 years	YES
Case study 2	18,21 years	13,0 years	NO

smaller than the battery life, with such a small difference between them, the investment would also be discouraged. Seeing that, the importance of finding the (economically) optimal size for the different applications regarding battery capacity in order to maximize the return on each investment in each case is justified [135].

Although in the cases analysed it is shown that the economic viability of the SESS installation behind the meter with the actual battery prices seems unattractive for investors, other studies have demonstrated that the SESS could play a relevant role in the economic results working in secondary electricity markets where benefits could increase significantly [136].

Note that the re-use of BEV batteries clearly offers an opportunity to enhance the circular economy way of thinking. If results are not dramatic (neither optimistic) when batteries are not even considered for re-use (which is the current case), they could certainly improve when eco-design comes into play. Moreover, not everything should end-up in economics. From an environmental perspective, it is said that the battery re-use decreases the impact of the battery per kWh exchanged through lifespan enlargement and it avoids the manufacture of new batteries for this same purpose.

9.4 Conclusions

First and foremost, this chapter was designed to validate the correct functioning of the model developed in Chapter 8. Secondly, it evaluates whether it is economically viable to install a SESS in two real cases of study in Spain using second life batteries that were previously used in a first life in the automotive sector.

This study combines the knowledge of the electricity market and strategies for reducing the price of the electricity bill using a SESS with knowledge of battery ageing. From this investigation, it can be concluded that an appropriate ageing model combined with an economical study is a mandatory requirement to determine the feasibility of installing a SESS.

In all the analysed cases, the study shows that the ageing of battery plays a relevant role in the economic results, although the price of batteries is the most important factor in determining whether the installation of a SESS is economically viable. Another very important point that can be highlighted from this study, is that in some cases, sizing only the battery to maximise savings on the electricity bill causes a large investment cost that cannot be recovered before the end of the battery's life. This work, after calculating all the costs of the electricity bill, also shows that the energy arbitrage strategy produces higher savings than peak shaving strategy as it also indirectly performs peak shaving.

It is also proved that the best economic return is obtained by over-dimensioning the SESS, which will require a lot of space to install the SESS and will increase the complexity of the installation.

Although the results obtained in this work do not present great economic savings, it is necessary to wait until the volume effect in the next few years causes a drop in the price of batteries so that all projects using second life batteries start to be attractive to investors. In addition, this will lead to greater investment in battery development that will also increase its energy capacity. If these two factors improve, the cases in which it will be economically interesting to install a SESS will increase. On the other hand, 2nd life batteries could reduce the effective price of EVs.

Chapter 10

Implementation of a 2nd life battery project

> Nothing in life is to be feared, it is only to be understood. Now is the timeto understand more, so that we may fear less.
>
> Marie Curie.

10.1 Introduction

According to the *"Agencia de Salud Pública de Barcelona"*, air pollution causes more than 350 premature deaths per year only in the city of Barcelona, being further a particularly relevant health problem for the most vulnerable population, such as the 200.000 children under the age of 14 who live in the city [137]. One of the main sources of pollution in cities are private vehicles [138], as a consequence, the expected entry of Electric Vehicles (EVs) (both (Battery Electric Vehicle (BEV) and Plug and Hybrid Electric Vehicle (PHEV))) into the transportation sector is seen as an unbeatable opportunity to reduce CO_2 emissions. Even so, the growth of EV sales, must be accompanied by an increase in electricity generation from renewable sources, otherwise CO_2 emissions will be displaced but not reduced.

On the other hand, although these renewable energy sources are eco-friendly, cheap and safe, their biggest problem is the intermittence. For instance, wind energy is only generated when there is wind. And solar energy is only generated when there is sun. This factor makes them incapable of supporting an electrical network on their own. Therefore, Stationary Energy Storage System (SESS) becomes a key and strategic element for the consolidation of renewable energy in the electricity sector. As a result, the demand for SESS is expected to increase considerably in the coming years [139]. In addition, the emergence of second life batteries in the energy sector will lead to a decrease in the price of batteries for static energy storage [43][44].

Consequently, once the reuse of batteries has been demonstrated through pilot projects (most of them led by Original Equipment Manufacturers (OEMs), with the support of electric companies), this chapter wants to go one step further and demonstrate the technical and economic feasibility of the use of 2nd life batteries in a domestic environment.

10.2 Technical characteristics

The objective of this is to describe the details of the battery used and the electrical installation that allows the integration of the project with 2nd life batteries in a house. Together with the battery, a system of solar panels for the generation of green energy is integrated into the project and a hybrid directional inverter has also been installed.

This installation has been designed to take advantage of the clean energy produced by the sun and to generate savings in the electrical bill. The battery allows the accumulation of energy produced through photovoltaic panels and to consume it at any time. Until today, the cost of batteries made their installation in a home barely feasible. The entry of reused electric car batteries into the energy market has led to a 50% reduction in the cost of batteries in comparison to using a new one. [43]. As a consequence, the use of batteries working as energy storage has increased considerably.

Historically, lead-acid batteries have always been used in static energy storage projects, because of their low cost. The cost reduction of Li-ion batteries, as a result of the entry of 2nd life batteries into the market, has finally led the market to opt for the use of Li-ion batteries. Li-ion batteries have better characteristics than lead-acid batteries, such as, higher energy density, lower self-discharge rate, fast charging, no memory effect, less weight, less maintenance and a lifetime three times longer. Furthermore, Li-ion batteries require a Battery Management System (BMS), an electronic element integrated into the batteries that serves to prevent accidents arising from the behaviour of lithium in its charging and discharging phases, provide battery safety and longevity, reveal state-of-function in the form of State of Charge (SOC) and State of Health (SOH), and indicate end-of-life once the capacity falls below the user-set target threshold.

Currently, and because of the numerous advantages of the Li-ion battery over the Lead-acid battery, the former has ended up imposing itself on the market.

The battery selected for this project, provided by BeePlanet [103], consists of 24 modules from used batteries of the Nissan Leaf in combination with a BMS designed specifically for SESS. Table 10.1 shows the main battery characteristics. It is important to highlight the Li-ion chemical variant used. Lithium Manganese Oxid (LMO) is notable for its low internal cell resistance that enables fast charging and high-current discharging which makes it perfect to be used in a SESS.

The photovoltaic installation is fixed and located on the roof of the house. Table 10.2 shows the main characteristics of a single solar panel. As fourteen panels have been installed, the total installed power is 5.180 Wp.

Finally, the last element of this installation, but not the least, is the inverter. In this case, a hybrid bidirectional inverter has been chosen because it allows the combination of photovoltaic generation and energy storage with no need for any additional Photovoltaics (PV) inverters. This inverter allows energy to flow in any direction. Photovoltaic $\leftrightarrow$ Battery, Photovoltaic $\leftrightarrow$ Electric Network, Battery $\leftrightarrow$ Electric Network.

The inverter already includes an Energy Management System (EMS). The EMS allows more advanced functionalities, such as self-consumption. Thanks to the built-in EMS, the installation can be monitored anytime via a PC or smartphone. The inverter is the element in charge of establish the direction of energy flow in order to minimise grid consumption. If the energy generated is greater than the demand, then any surplus energy could either be used to charge the batteries or to be injected into the grid. Table 10.3 shows the main characteristics of the inverter.

Table 10.1: Battery characteristics [103]

Manufacturer	**BeePlanet Factory ®**
Chemistry	LMO
Number of modules	24 modules
Rated capacity	8000 Wh
Rated capacity	90 Ah
Energy density	67 Wh/kg
Nominal power	5000 W
Nominal voltage	90 V
Working voltage	72 V – 100 V
Peak current	72 V – 100 V
DOD	90 %
Estimated equivalent cycles	$>$ 2000 cycles
Communications	BUS CAN, Bluetooth
Working temperature	5ºC - 40ºC

Table 10.2: Solar panel characteristics [140]

Manufacturer	**Powitt Solar Energy ®**
Model	PW-6M72-370
Peak Power Watts-Pmax	370 Wp
Power Output Tolerance-Pmax (%)	0/+5
Maximum Power Voltage - V_{MPP}	39,7 V
Maximum Power Current - I_{MPP}	9,33 A
Open Circuit Voltage - V_{OC}	48,3 V
Short Circuit Current - I_{SC}	9,83 A
Module Efficiency η_m	19,1 %

Table 10.3: Inverter characteristics [141]

Manufacturer	**Ingeteam ®**
Model	IS STORAGE 1Play
Battery input (DC)	
Voltage range	40 - 450 V
Maximum current	66 A
Type of battery	Lithium-Ion
PV input (DC)	
PV array maximum power	11,5 kWp
Maximum input voltage	550 V
Grid input (AC)	
Rated voltage	230 V
Maximum input voltage	550 V
Nominal Frequency	50 / 60 Hz
Rated power	6 kW

Figure 10.1 shows the electrical diagram of the installation in detail including how the three mentioned components are connected to each other. The solar panel configuration consists of two strings of seven panels in series each leading to a working voltage of 280 V. The two strings are connected directly to each of the Maximum Power Point Trackings (MPPTs) input of the inverter on the DC side. The battery is also connected to the DC side of the inverter. The figure also shows that, the solar panels, the battery and the inverter have their own electrical protection. In addition, the inverter is connected by the AC side directly to the general electrical panel of the house.

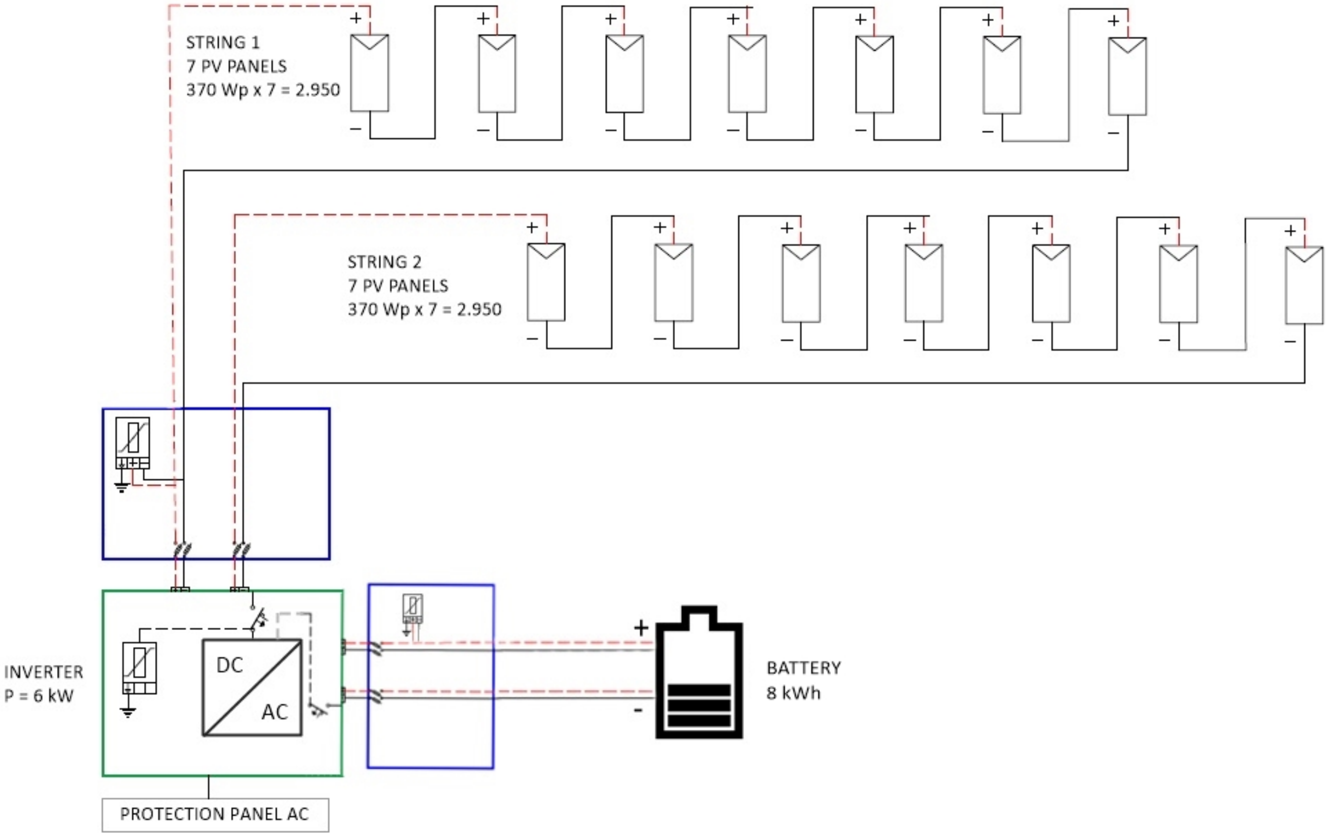


Figure 10.1: Electrical diagram of the installation

10.3 Performance and economic results

Since the installation was launched at the end of August 2020, only the results from September and October are available. As during winter months solar production is expected to drop, this installation has been designed to cover most of all consumptions for this season. Consequently, an overproduction is already foreseen for the summer season, since sunlight hours are longer.

Figure 10.2 displays a typical three day performance of the installation. Light grey shows the solar generation that is directly consumed by the house. Dark blue represents the solar generation that is used to recharge the battery. Light blue illustrates the battery discharging directly to the household consumption. Dark grey shows the solar generation that is not used and is sold to the grid. Finally, orange describes the energy consumed from the grid.

In addition, apart from the consumption, the SOC of the battery is displayed. According to the technical characteristics shown in Table 10.1, a Depth of Discharge (DOD) of 90% is observed.

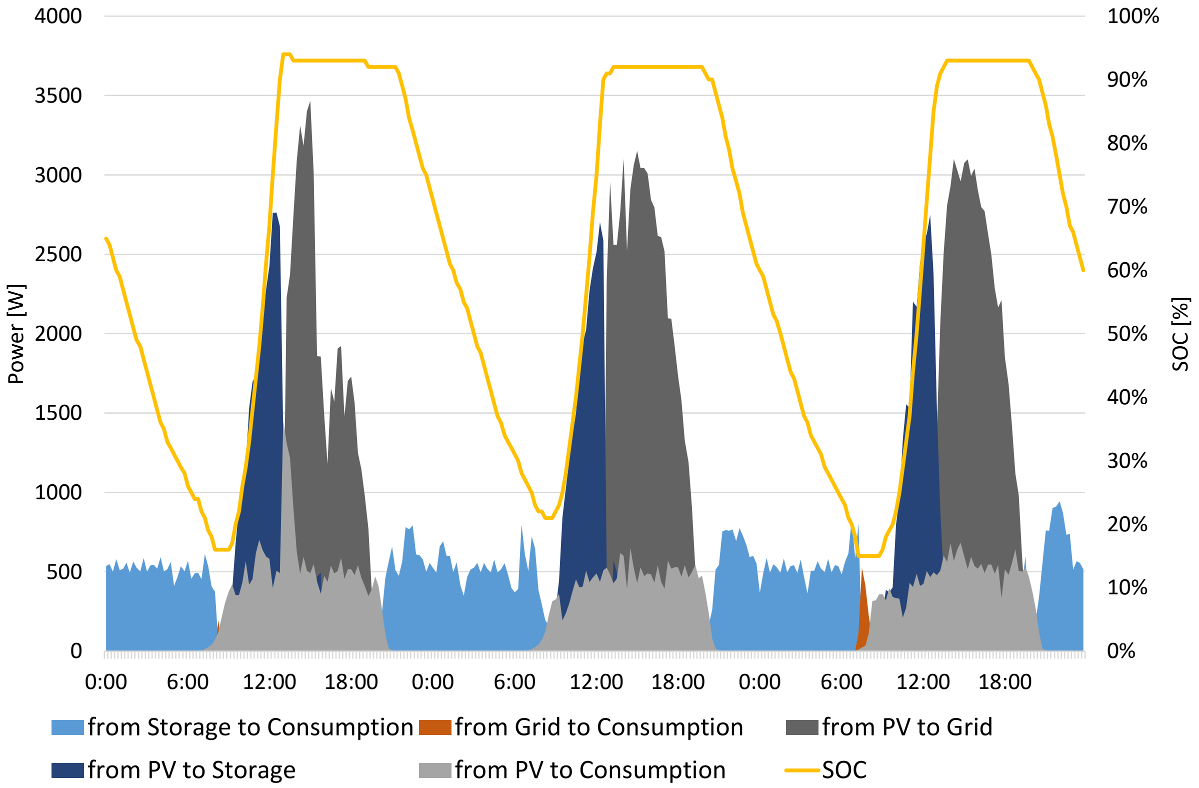


Figure 10.2: Typical three days performance

Table 10.4 compares the energy consumed and the associated costs during those months with and without solar panels and battery. When there is neither battery nor PV, all the energy consumed by the house comes from the electricity grid, 424 kWh in September, 361 kWh in October. To obtain the cost of energy in each month, these kWh are multiplied by the cost of energy, being 0,12€/kWh. Resulting 50,93€ in September and 43,37€ in October. To these amounts, power cost and taxes are added to obtain a total invoice cost of 130,91€ and 114,11€ respectively.

On the other hand, when in the electricity bill simulation the battery and the PV are considered, the results are very different. In this case, the consumption of the electricity grid descends to 74 kWh in September and 77 kWh in October. This means a reduction of 82% and 78% in that order. Apart from that, now, the energy consumption is divided between solar generation and battery discharge. In September the energy produced by the PV that was directly consumed was 170 kWh, and the energy discharged by the battery was 180 kWh. In addition, the overproduction of solar energy led to the sale of a total of 343 kWh to the electricity grid. As far as October is concerned, 119 kWh were consumed directly from solar generation, 165 kWh discharged from the battery and 282 kWh sold to the grid. As clearly shown, the inclusion of the battery and PV in the simulation result in a large reduction in the monthly cost of the electricity bill, costing 87% less in September, and 82% less in October. One factor to consider is the price of energy sold to the grid, which, having taken the average price during the months analysed, is 0,03 €/kWh [142]. Another decisive aspect when calculating the cost of the electricity bill, according to the *"Real Decreto 244/2019"* [143] which regulates the administrative, technical and economic conditions for the self-consumption of electricity, is that the difference between the energy bought and the energy sold can never be favourable to the customer. This means, as seen in September, that when the cost of energy sold exceeds the cost of energy bought, the cost will be set at zero euros.

Table 10.4: Electricity bill simulations

	September		October	
	w/o PV & batt	w/ PV & batt	w/o PV & batt	w/ PV & batt
Grid energy consumed [kWh]	424	74	361	77
PV energy consumed [kWh]		170		119
Battery energy discharged [kWh]		180		165
Energy sold [kWh]		343		282
Power cost	14,58 €	14,58 €	14,58 €	14,58 €
Energy bought	50,93 €	8,88 €	43,37 €	9,28 €
Energy sold		- 10,29 €		- 8,47 €
Energy cost (bought - sold)	50,93 €	- €	43,37 €	0,81 €
Taxes	14,46 €	3,22 €	12,79 €	3,40 €
Total bill cost	**130,91 €**	**16,39 €**	**114,11 €**	**19,59 €**

It is important to note that this chapter examines the economic viability of installing a SESS using 2nd life batteries. Therefore the cost of setting up the PV is completely outside of the scope.

Then, using equations 8.6, 8.7, 8.8,8.9 and 8.10 from Chapter 8, and also taking in consideration the costs detailed in Table 10.5 we can determine the cost of the SESS used in this project. The cost of installing the SESS is 1.100€.

Table 10.5: SESS costing [42]

		Cost
Specific cost per storage	50 €/kWh	400 €
Specific cost per power	80 €/kW	400 €
Specific cost per material	30 €/kW	150 €
Specific cost per labour	30 €/kW	150 €
Total cost		**1.100 €**

Consequently, to calculate the Return of Investment (ROI) of installing a SESS only the energy discharged by the battery is counted. Thus, taking the average energy discharged from the battery during the two analysed months (172 kWh), and multiplying them by the cost of energy plus taxes, 20,70€ can be saved each month. Then, in order to determine if the investment is feasible, solving the equation 10.1, the ROI is estimated.

$$\text{ROI} = \frac{\text{SESS}\ Cost\ Investment}{Savings} = \frac{1.100\ €}{20,70\ €} = 4,42\ Years \tag{10.1}$$

On the other hand, regarding the battery ageing, the house electricity consumption curve is introduced in the battery ageing model with the aim of estimating the lifespan of the SESS. As Figure 10.3 shows, the useful life of the SESS is 8 years.

In view of the above results, we can conclude that the installation of this SESS is viable since its lifespan is three years longer than its payback. However, as it is only available for two months of operation, it has not been possible to empirically analyse the degradation of the battery. This will mean that as the battery reduces its capacity, the calculated monthly savings on the electricity bill will be reduced, which will have a direct effect on the calculation of the ROI, which could be slightly increased.

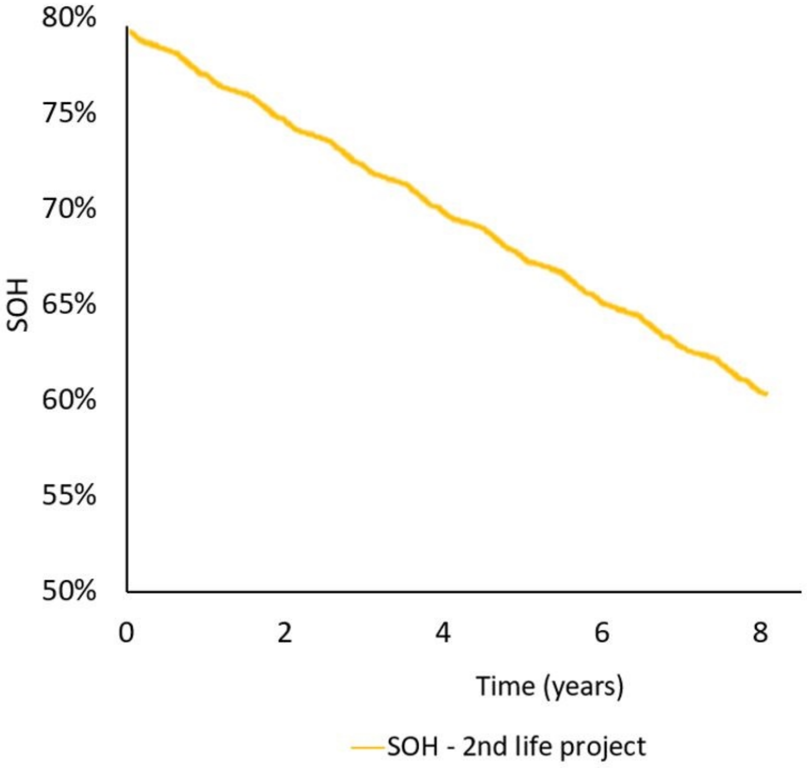


Figure 10.3: Cell capacity fade

10.4 Conclusions

Once the technical and economic feasibility of using battery's 2nd life as a SESS has been extensively studied and demonstrated in several pilot projects, this chapter analyses the implementation of a 2nd life battery project in a house.

On account of the short time that the installation has been functioning, it is difficult to draw satisfactory conclusions. Nevertheless, this project serves to demonstrate that the technology is sufficiently mature to enter to the static energy storage market.

Furthermore, it has also been demonstrated that the use of a SESS is a perfect complement to PV systems for private houses, due to the fact that it allows the ratio of green energy use to be increased and also that it leads to significant economic savings in the electricity bill. On the other hand, the ROI concludes that any lifetime of the battery higher than the lifespan of the battery will make the installation viable from an investment point of view.

Chapter 11

Comparison of the state of Lithium-Sulphur and Lithium-Ion batteries applied to electro-mobility

> We should be taught not to wait for inspiration to start a thing. Action always generates inspiration. Inspiration seldom generates action.
>
> Frank Tibolt.

11.1 Introduction

The market share in Electric Vehicles (EVs) is increasing. This trend is likely to continue due to the increased interest in reducing CO_2 emissions. The electric vehicle market evolution depends principally on the evolution of battery capacity. As a consequence, automobile manufacturers focus now their efforts on launching in the market EVs capable to compete with Internal Combustion Engine Vehicles (ICEVs) in both performance and economic aspects. Although EVs are suitable for the day-to-day needs of the typical urban driver, their range is still lower than ICEV, because batteries are not able to store and supply enough energy to the vehicle and provide the same autonomy as ICEV.

EV use mostly Lithium-ion (Li-ion) batteries but this technology is reaching its theoretical limit (200–250 Wh/kg). Although research to improve Li-ion batteries is very active, other studies have begun to investigate alternative electrochemical energy storage systems with higher energy density. At present, the most promising technology is the Lithium-Sulphur (Li-S) battery.

This chapter presents a review of the state of Lithium-Sulphur battery on EVs compared to Li-ion ones, considering technical, modelling, environmental and economic aspects with the

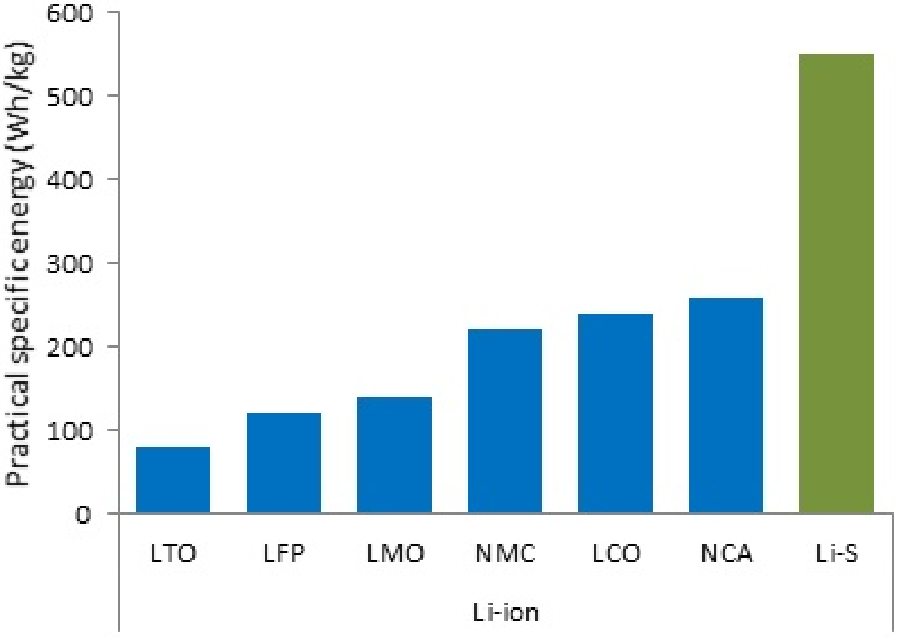


Figure 11.1: Comparison of the Practical Specific Energy (Wh/kg) of Li-ion and Li-S.

aim of outlining the challenges this technology has to overcome to substitute Li-ion in the near future. This study shows how the main drawbacks for Li-S concern are durability, self-discharge and battery modelling. However, from an environmental and economic point of view, Li-S technology presents many advantages over Li-ion.

11.2 Results and Discussion

This section is divided into four subsections. The first one analyses technical aspects of the Li-S batteries based on their the physical and chemical characteristics compared to Li-ion, the second part focuses on battery models in relation to BEV applications and the third and fourth subsections show the results obtained from the review of the environmental and economic aspects of Li-S cells and batteries for Battery Electric Vehicle (BEV) applications respectively.

11.2.1 Chemical and physical characteristics

Li-S technology is not just another modification of the Li-ion chemistries; the replacement of metals by Sulphur in the cathode makes them perform in a different manner. Thus, many concepts learned from Li-ion cannot be implemented in Li-S batteries due to the different chain of chemical reactions that take place.

Li-ion cells have just one chemical reaction: Lithium ions insert into the molecular structure of the carbon electrode (intercalation) all through the discharge process. On the contrary, in Li-S cells, Sulphur reacts with Lithium ions when reduced from elemental state S_8, via the intermediates Li_2S_8, Li_2S_4, Li_2S_2, to Lithium sulphide Li_2S depending on the SOC [144][145].

Nowadays, Li-S batteries practical energy density is considered to be between 200 and 500 Wh/kg (Table 11.1 and Figure 11.1) which lower limit is within the current values obtained for high performance packs.

It seems that all chemistries based on Li-ion have a correlation between the theoretical energy density and the accessible practical capacity of three times less [109][146][147][148]. On the other hand, the theoretical capacity of Li-S battery is 1675 mAh/g making its theoretical gravimetric energy density 2600 Wh/kg [149][150], so the actual correlation for Li-S between theoretical and practical energy density is around ten times less, as shown in Table 11.1, it being at the very beginning of the learning curve and having a strong potential to improve current battery performances. Assuming that the relation between theoretical and maximum practical energy density hardly ever exceeded the 1/3 [147] it can be confirmed that Li-ion batteries are effectively reaching their practical energy density limit while Li-S, with a current state of 200 – 500 Wh/kg have still a large margin to improve their practical capacity, concluding that the practical specific energy of Li-S could reach in a near future almost 900 Wh/kg, which is more than four times the current value of Li-ion batteries.

Additionally, apart from the better capacity Li-S cells have, these are able to work throughout all State of Charge (SOC) windows from 0% to 100%. This is a significant opportunity to exploit all the capacity, instead, Li-ion cells have to leave a margin of safety reducing the window work by approximately 20% of SOC[151].

Table 11.1: Comparison of the characteristics of Li-ion and Li-S cells and batteries

	Li-ion				**Li-S**
	NMC	NCA	LCO	LFP	
Cell voltage [V]	3,7	3,6	3,65	3,2	2,15
Theoretical specific energy [Wh/kg]	400-600	400-600	400-600	300-400	2600
Practical specific energy [Wh/kg]	220	260	240	120	200–550
Practical/Theoretical correlation	1/2,5	1/2,6	1/2,7	1/2	1/10
Power density [W/l]	320	270	450	200	100-200
Cycle life [cycles]	1000–2000	500	700	1000–2000	50
Self-Discharge Rate [month]	1%	1%	1%	1%	8-15%
Thermal runaway [^{o}C]	210	150	150	270	120
Work window [SOC]	15 – 95 %	15 – 95 %	15 – 95 %	15 – 95 %	0 – 100 %
Memory effect	No	No	No	No	Yes

Table 11.1 and Figure 11.2 depict that although Li-S technology has a better theoretical specific energy than Li-ion and also a very good margin to improve its practical specific energy, there are also some other factors that are far from overtaking Li-ion chemistry properties.

While in Li-ion batteries, cathode materials range varies from Lithium Cobalt Oxide, Lithium Manganese Oxid, or Lithium Nickel Manganese Cobalt Oxide, among others [152], elemental Sulphur is the main cathode material in Li-S and this is closely related to its structure and electrochemical properties [149]. Li-S batteries, as well as Li-ion batteries, use Lithium on the anode due to its extremely high theoretical specific capacity of 3860 mAh/g and the lowest negative electrochemical potential of -3,040 V [25]. Although Li-S battery present many advantages that make it a suitable candidate for EVs applications, the low conductivity of sulphur ($5x10^{-30}\ S/cm\ at\ 25^{\circ}C$) [153] and the expansion of the cathode upon lithiation and the solubility of Sulphur and of Lithium polysulphides in the electrolytes cause of many effects such as self-discharge, short cycle life and too-low coulombic efficiency [25][154] negatively affecting the performance of the battery. The expansion of the cathode occurs because of the different molar volumes of Lithium sulphide and polysulphides compared to Sulphur (80% greater). Partial dissolution of polysulphides causes anode corrosion and leads to the formation of shorter polysulphide compounds. Short polysulphides, in turn, diffuse and migrate to the cathode where they re-oxidize or react with the solid Sulphur at the cathode to form longer polysulphides, initiating a shuttle mechanism, which leads to low energy-conversion efficiency [154]. In the case of high-loading

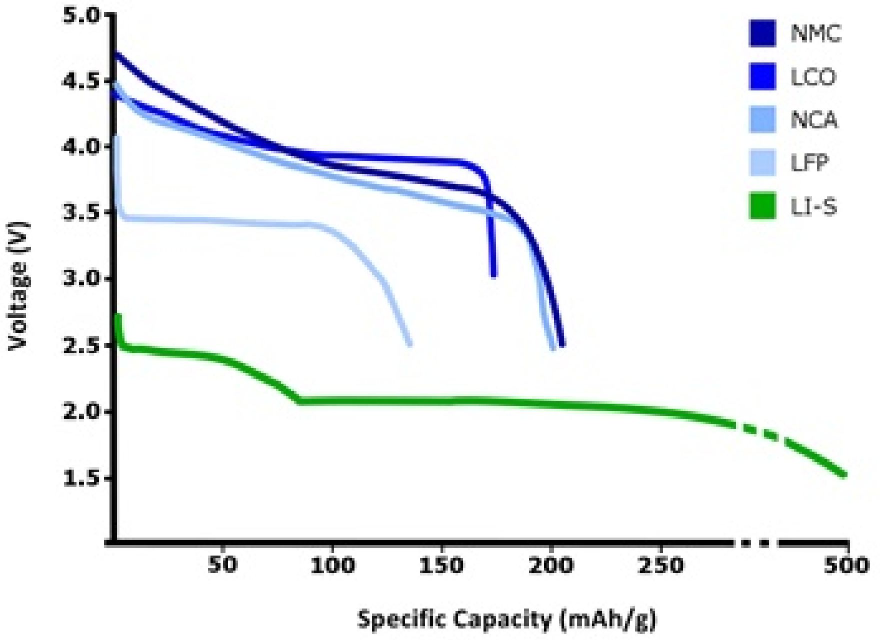


Figure 11.2: Discharge curves of Li-S and different Li-ion chemistries

Li-S batteries, the shuttle effect will be more serious as the polysulfide crossover is multiplied [155]. In fact, shuttle effect occurs more at low and uniform charging current rates [155].

In order to mitigate the effect of the low conductivity of Sulphur, some research proposes downsizing the Sulphur to nanosize particles and adding a large amount of carbon. However, this method unfortunately sacrifices the energy density of the Li-S cells due to the fact that high fractions of light carbon materials like porous carbon or Carbon Nanotube (CNT) lower the volumetric energy density considerably. For instance, if the carbon content achieves around 30 % of the total cathode weight, the energy density of the cell can decrease c.a. 25 % [150]. This is a relevant drawback when designing energy storage systems for portable applications such as EVs [156].

Furthermore, in order to reduce the effect of the cathode expansion it has been proposed to assemble a Sulphur battery in a fully-lithiated state by using Li_2S as an active cathode material as it enables combining safer, Lithium-metal-free anodes and eliminates expansion and breaking of the cathode on lithiation [157].

In parallel, several research studies have been conducted to mitigate the negative effect of the polysulphide shuttle. Much of this work has focused on either the protection of the Lithium anode or on the restriction of the ionic mobility of the polysulphide anions. However, since protection of the Lithium anode causes a slow reaction rate at the anode during the discharge cycle due to passivation of the anode, this leads to a loss of power density in the battery. Gel electrolytes and solid electrolytes have been reported as a means of slowing down the polysulphide shuttle by reducing the ionic mobility of the electrolytes [158]. Another solution proposed is to use $LiNO_3$ on the anode to promote the formation of a stable passivation film, which is known to significantly suppress the redox shuttle of Lithium polysulphide. $LiNO_3$ is beneficial to Li-S battery only when its irreversible reduction on the cathode is avoided, which can be easily achieved by raising the discharge cut-off voltage [159][160][161][162] although the exact nature of the $LiNO_3$ functionality is still unclear [163].

Besides the chemical properties and inherent trade-offs, Li-S batteries present a unique charge and discharge mechanisms, that at the moment has not been fully characterised [25][146], though, *Abbas Fotouhi et al.* explain the working principles of Li-S battery. In the discharge phase, solid

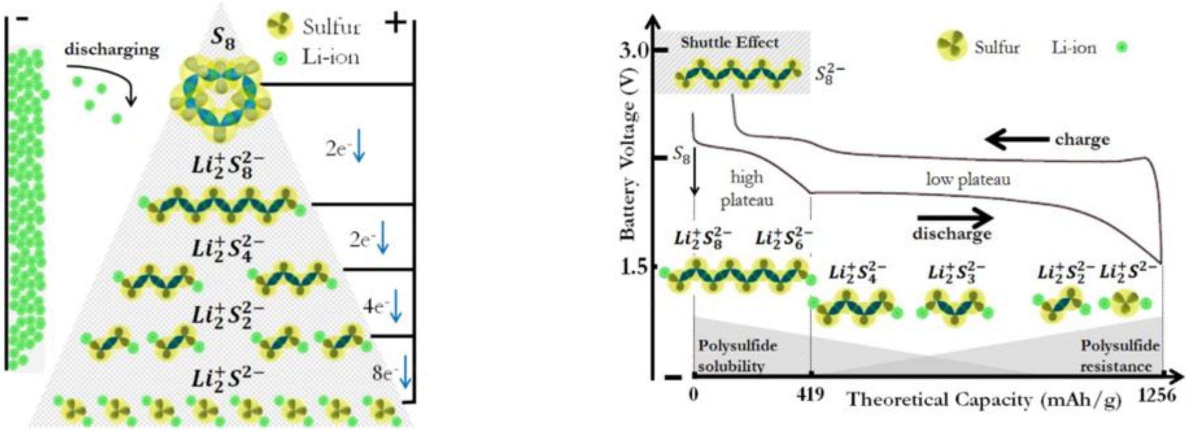


Figure 11.3: (Left) Working principle of Li-S battery. (Right) Basic voltage behaviour Li-S Battery [145]

Sulphur from the cathode dissolves into the electrolyte, forming S_8. Then, redox reactions take place. Intermediate products are formed at the cathode through a reduction, called lithium polysulfide species $Li2Sx$. Instead, at the anode is produced an oxidation of Li metal to Li+ ions. At the end of discharge, S_8 is fully reduced to S^{2-} (Li_2S) and the anode is fully stripped of Li metal. On the other hand, in the charge phase, the reactions take place in the opposition direction, with Li+ ions depositing at the anode as Li metal and low-order polysulphides oxidizing from S^{2-} up to S_8^{2-} and eventually S_8(s) [151]. This process is illustrated schematically in Figure 11.3.

In fact, Figure 11.3 presents the differences of Li-ion and Li-S in relation to the discharge curve. While Li-ion have an almost continuous decrease of voltage against SOC, Li-S have a high plateau at about 2,35 V (OCV), with a majority of high order polysulphides in solution (Li_2S_8, Li_2S_6) and a low plateau at around 2,1 V (OCV), with a majority of low order polysulphides in solution (Li_2S_4, Li_2S_3, Li_2S_2, Li_2S) [145]. These dips and rises in the discharge curve might cause problems to state of charge calculation [164]. These SOC estimation difficulties will be assessed in section 11.2.2 when studying the battery models.

Power limitations of Li-ion batteries are governed by the diffusion of ions into the electrodes, which is mainly defined by the battery design and therefore not considered to vary rapidly with normal usage. On the other hand, for Li-S batteries, power exhibits a high sensitivity to cycling parameters such as current profile or temperatures due to slow diffusion of species through the electrolyte, bottlenecks in the electrochemical reaction pathway and reduced availability of active species and/or active surfaces (for instance, due to the precipitation of lower order polysulphides). Polysulphide kinetics in the high plateau region are fast, leading to good rate capabilities and low cell resistance, but the high plateau usually accounts for merely 10%-30% of a cycled cell's capacity.

Additionally, polysulphides kinetics are directly related to cell voltage Figure 11.3, represents the OCV against SOC. In Li-S, voltage ranges between 2,7 V when fully charged to 1,5 V when depleted. These values are almost half of those from Li-ion, directly affecting the power rates. Therefore, although Li-S have higher energy density they have lower power density than Li-ion, which is a primary concern for car manufacturers [165][166][167]. With respect to current rates, recent studies [168] have shown that Li-S cells present low values compared to Li-ion. In fact, while Li-ion cells can achieve 20-50 Ah/cell, Li-S values are about 10 times lower. This characteristic is a major issue when configuring a battery pack for EVs application. For instance, for Li-ion technology, a 90kW battery can be obtained by connecting around 100 cells at 3,8 V, while it is unclear how to achieve these values, with Li-S cells without achieving high C-rates.

Therefore, Li-S cells low power and high capacity as shown in Figure 11.3 make this chemistry more suitable for EVs than for PHEV's [169].

Another important aspect that Li-S should improve concerns the number of cycles they can do. Long life cycles are essential for car manufacturers, as battery warranties ensure eight to ten years or 100.000 to 150.000 km [170]. Nowadays, Li-S batteries have extremely rapid decrease in capacity, lasting for less than 50 cycles [171][172], which is between 10 and 40 times less than what Li-ion commercial batteries are offering (Table 11.1). Moreover, Li-S batteries have 8-15% self-discharge rate per month [172][173] due to polysulfide shuttle [174] and collector corrosion [165][175][176], which is between 10 and 15 times higher than the self-discharge of Li-ion batteries (Table 11.1). *Yousif et al.* conducted tests under different conditions on a 21 Ah Li-S cell, which showed that self-discharge is more significant as SOC increases [177]. Thus it is recommendable to store Li-S batteries at low SOC. Nonetheless, most of the applications need a battery fully charged as a starting operational point.

Even though, as explained above, the shuttle effect has several undesired consequences on Li-S batteries, *Vaclav Knap et al.* make use of this effect to introduce a new type of passive dissipative balancing method, based on electrochemistry, which allows one to take better advantage of the total capacity. This intrinsic self-discharge phenomenon of Li-S batteries can be used for dissipating the energy of the unbalanced cells with higher charge [178].

As it has been explained, Li-S inherent differences compared to Li-ion lead to significant performance divergences. The shuttle effect leads to low coulombic efficiency and short lifespan. Therefore, one of the major issues is the one related to the low voltages and C-rates that Li-S can achieved, despite the high energy voltages, compared to Li-ion that represent a challenge for BEV applications.

11.2.2 Modelling

Battery models for EV applications need a good balance between response speed, reliability and complexity. The differences in the working principle between Li-ion and Li-S technologies also affect battery modelling. Modelling is used to study battery designs and dimensioning in vehicles or in other stationary applications under different working conditions (temperatures, Depth of Discharge (DOD), C-rate, etc.) without the need to perform costly and time consuming experimental tests for each case [64]. In the case of EVs, battery models are useful for practical and real time issues, such as indicating the available range to drivers, or for vehicle design, such as thermal management, lifespan estimation or performance optimization among others [65]. Thus, this study assumes that battery models for EV applications are focused on functional and external parameters rather than on the understanding of its chemical behaviour. Regarding batteries, most of the models are based on mathematical, electrochemical and electric equivalent approaches.

While Li-ion batteries models are quite advanced and precise, those of Li-S are still in an embryonic stage due to the novelty of this technology and they are producing unpredictable behaviours that should be thoroughly analysed.

One of the main issues in battery modelling is SOC estimation, which in Li-ion batteries is preliminary done by Coulomb counting and voltage reading. Coulomb counting registers the amount of current passing through the battery and it can be applied while the battery is in use. However, measurements have an error that increases over time. Therefore, whenever the conditions are stable enough, SOC estimation is calibrated by means of a voltage measurement. These two methods don not apply to Li-S because coulomb counting fails as the shuttle effect and voltage reading might be misleading as a consequence of the two plateaux (non-linearity).

Temperature is another important factor that influences the voltage of the battery and in consequence the usable capacity, power, SOC estimation, etc. The effect of temperature in Li-ion batteries has been fully studied and today it is possible to predict and reproduce its dependence on voltage and lifespan [74][179].

In parallel to the difficulties in predicting the battery behaviour due to temperature, Li-S models should also take into account memory effect that are not fully characterized yet for Li-S technology. This problem is inexistent in Li-ion batteries. Therefore, although Li-S batteries have potential to work well in cold environments, the relationship between OCV and temperature may change substantially depending on previous cycles due to memory effect [145].

Despite the differences, Li-S and Li-ion batteries models present the same factors. For example, in instant response models it might be enough to use voltage, temperature and C-rate to evaluate the behaviour of a battery. However, for battery ageing and cycling degradation, models should include other factors such as DOD and the effect of time on the calendar ageing.

Regarding mathematical models, they can be both analytical and stochastic. In the first one, few equations are used to describe battery properties. Stochastic battery models, are based on the principle of the discrete-time Markov chain where one can predict the future of the process based on its present state without knowing its full history.

Electrochemical models are extremely accurate but at the same time overly complicated, needing greater capacity for data processing [67], hence, they are not suitable for EVs. On the other hand, Electrical Circuit Equivalent (ECN) models are accurate enough and have a lower complexity. Its fast response offers them the chance to work in real time conditions making them suitable for automotive applications.

Similarly, *Hongwen et al.* also made a comparison between the electrochemical and the ECN models concluding that ECN model performs much better for EV applications [180]. *Abbas Fotouhi et al.* in [144] compares and analyses the three different battery modelling approaches (mathematical, electrochemical and ECN) both for Li-ion and Li-S, concluding that despite electrochemical models have the potential to offer extreme accuracy ECN models are more suitable to predict the battery behaviour for EV applications, as they can support parametrisation of different operating points and therefore they can be used to estimate SOC.

Table 11.2 presents a summary of the different Li-S models classified by type and ordered per year. This chronologic order shows the fact that mathematic models are the first used when a new chemistry is under development. Usually this first stage is performed at cell level. After that, the electrochemical model gains relevance in both cell and battery level to better understand the chemical reactions inside.

Table 11.2: Li-S models classifieds by the type of model

Author	**Year**	**Level**	**Objective**	**Ref.**
Chen	2006	Battery	Prediction of the remaining battery capacity of Lithium-ion batteries	[181]
Karthikeyan Kumaresan	2008	Cell	Physical reasons for the two-stage discharge profile	[182]
O. Erdinc	2009	Battery	Effects of temperature and capacity fading	[183]
Suguna Thanagasundram	2012	Cell	Cell model for battery simulation	[148]
Mahmoudreza Ghaznavi, P. Chen	2013	Cell	Applied discharge current and cathode conductivity	[184]
Natalia A. Cañas	2013	Battery	Equivalent circuit model using electrochemical impedance spectroscopy	[185]
Zhaofeng Deng	2013	Battery	Modelling and Analysis of Capacity Fading	[186]
Andreas F. Hofmann	2014	Battery	Shuttle and capacity loss	[155]

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Table 11.2 – *Continued from previous page*

Author	**Year**	**Level**	**Objective**	**Ref.**
Mahmoudreza Ghaznavi, P. Chen	2014	Cell	Precipitation reaction kinetics and Sulphur content	[187]
Mahmoudreza Ghaznavi, P. Chen	2014	Cell	Variation of the exchange current densities, diffusion coefficients, and cathode thickness over a wide range	[188]
Martin Rolf Busche	2014	Cell	Shuttle-effect at different temperatures and different rates	[189]
Monica Marinescu	2015	Battery	Dimensional model during charge and discharge	[176]
Teng Zhang	2015	Cell	Modelling the voltage loss mechanisms	[190]
Vaclav Knap	2015	Battery	Parametrization Techniques for an Electrical Circuit Model	[191]
Vaclav Knap	2015	Battery	Performance Modelling	[192]
Abbas Fotouhi	2015	Battery	Electric Vehicle Battery Model Identification and State of Charge Estimation in Real World Driving Cycles	[193]
Abbas Fotouhi	2016	Battery	Prediction-Error Minimization (PEM) algorithm applied to experimental data	[194]
Y.X. Ren	2016	Battery	Discharge behaviour incorporating the effect of Li2S precipitation	[195]
Vaclav Knap	2016	Battery	A self-discharge model based on direct shuttle current measurement	[175]
Abbas Fotouhi	2016	Cell	Graphical User Interface for Battery Design and Simulation; From Cell Test Data to Real-World Automotive Simulation	[196]
Abbas Fotouhi	2016	Battery	Model in real-time applications where accuracy is important	[197]
Karsten Propp	2016	Battery	Non-linear state-of-charge dependent ECN model	[145]
Ali Abdollahi	2017	Battery	Optimal charging for general equivalent electrical battery model, and battery life management	[198]
Abbas Fotouhi	2017	Cell	Equivalent Circuit Network Model Parameterization and Sensitivity Analysis	[199]
Vaclav Knap	2017	Battery	Model to study the self-balancing feature	[178]
Mahsa Ebadi	2017	Battery	Modelling the Interfacial Chemistry of the LiNO3 Additive	[163]
Daniel-Ioan Stroe	2017	Battery	Modelling the discharge phase	[200]
Abbas Fotouhi	2017	Battery	SOC observability Analysis and Estimation	[201]
Peng Tan	2017	Battery	Mass transport and electrochemical reaction processes is first developed	[202]
S. E. A. Yousif	2018	Battery	Self-Discharge Effects in Lithium-Sulphur Equivalent Circuit Networks	[177]

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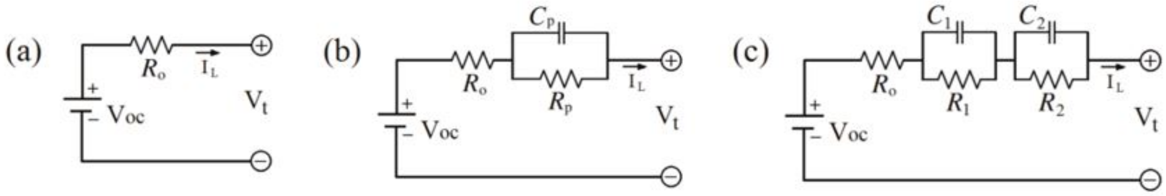

Figure 11.4: ECN battery model structures: (a) R model, (b) 1RC model, (c) 2RC model

Table 11.2 – *Continued from previous page*

Author	**Year**	**Level**	**Objective**	**Ref.**
Monica Marinescu	2018	Battery	Irreversible vs Reversible Capacity Fade during Cycling: The Effects of Precipitation and Shuttle	[203]
Saul Perez Beltran	2018	Battery	New understanding of graphene effects on S reduction behaviour	[204]
Nisa Erisen	2018	Battery	Predict the effect of critical cathode design parameters	[205]
Vaclav Knap	2018	Battery	Test Methodology for Degradation Assessment	[206]

Due to the computational limitations of the microprocessors on board EVs and that they execute many tasks besides those related to the battery; battery models implemented on EV should demand low computational resources. Thus, once the chemical functionality of the battery is understood, simplified models are better options and, for this reason, ECN models take the lead.

The parameters obtained with ECN models are directly usable in applications to know SOC, SOH, voltage and the internal resistance of the battery, all these parameters are necessary for the sizing of a battery in EVs [191].

The ECN model is constructed using elementary electrical components: resistors, capacitors and voltage sources in a circuit, as shown in Figure 11.4. The essential configuration of an ECN battery model is using only one resistor and one voltage source to make a circuit Figure 11.4a) which simulate exclusively the internal resistance of the battery. Adding RC (Figure 11.4 b,c) pairs to the model increments its accuracy by taking into account the battery polarization characteristics [196]. It is essential to accurately parametrize the different elements in the ECN model to obtain reliable results. The extensively used methods to parametrize the ECN elements are current pulse-based methods [171][207] and the electrochemical impedance spectroscopy (EIS). [208][209][210]. Another difference between Li-ion and Li-S is that the last one, the voltage profile is substantially distinct between charge and discharge.

As a general conclusion, models for Li-ion are not transferable to Li-S model due to their differences in performance. The automotive sector is interested in simple and fast models such as ECN. However, as shown in Table 11.2, most recent studies are still struggling with electrochemical models, indicating that this technology needs more testing to be fully understood to, afterwards, develop reliable ECN models. Therefore, the current knowledge in Li-S battery behaviour has to improve in order to be applied in such ECN models and, it needs to be improved for its further application in EVs.

Additionally, in contrast to Li-ion batteries, the memory effect is a factor that should be considered carefully for Li-S modelling as it can have a major influence on the cycles, above all in cold environments.

11.2.3 Environmental analysis

Li-S batteries are theoretically considered to have lower environmental impact due to the use of Sulphur, which is an element relatively abundant on Earth, which makes it a non-toxic inexpensive material [154]. Nevertheless, this potential advantage is not fully assessed in most of the available literature concerning this technology. While there is a large number of articles that analyses Li-ion batteries from an environmental perspective, one hardly finds the same type of information for Li-S. Therefore, this paper includes a review of the findings found in some few articles regarding the environmental performance of Li-S compared to Li-ion batteries.

It should be noted that in all the references, Life Cycle Assessment methodology (LCA) has been applied as it enables a holistic characterisation of the environmental performance of the batteries. For a consistent environmental assessment, LCA should define clear boundary conditions to delimit the scope of the analysis and then consider all the steps within, such as raw materials acquisition, energy consumption to produce parts, transportation, etc... LCA studies may then cover life cycle stages up to the production of the battery (cradle-to- gate studies) or their full life cycle, including use-phase and end of life (cradle-to- grave).

The environmental impact of actual Li-ion batteries is said to be responsible for almost half of the whole environmental impact of the EV manufacture. Then, during the use-phase, the environmental impact of the EV strongly depends on the electricity mix of the country where batteries are used [211][212] and the lifespan of the battery.

To produce cathode materials for Li-ion batteries, *Dunn et al.* indicated that the energy consumption was considerably different for each Li-ion technology. In their study, LMO cathodes were the ones with lower energy consumption, followed by LFP cathodes that consumed half of the energy required for NMC cathode production. LCO cathodes were the ones having higher consumption, between 3 to 5 times more energy demand than LFP [213]. Similarly, the United States Environmental Protection Agency [214], studied the environmental impact of LMO, LFP and NMC electric vehicle batteries declaring that NMC cathode materials required 1.4-1.5 times as much primary energy consumption as the other two technologies. However, in contrast to the analysis from Dunn et al., this study did not only study the amount of energy needed to build these cathodes but also analysed the stages of materials extraction, processing and manufacture, indicating that NMC batteries use rare metals such as Cobalt and Nickel that entail high human toxicity impacts in comparison to the other two chemistries using manganese and iron [28].

Although it was common to analyse the environmental impact regarding only the Greenhouse Gas (GHG) emissions taking the kg of equivalent CO2 emitted as the key indicator, nowadays, most environmental studies consider additional impact categories, such as materials depletion potential, toxicity and fossil resource depletion, among others.

Within these recent approaches literature agrees that LFP and LMO batteries have lower environmental impact than other Li-ion technologies. In fact, LMO performs better in some of the environmental impact categories while LFP does it in others, having a similar overall total impact [215] except from the study by *Hawkins et al.* that considered that the impact from Lithium Iron Phosphate (LFP) and NMC batteries was similar [216].

The EV battery manufacture cradle-to-gate review from Kim et al. also concluded that the Global Warming Potential (GWP) of NMC batteries was between two and three times higher than those from LMO [217]. And the overall comparison of several technologies from lead acid to Li-ion batteries by Sullivan and Gaines [218] concluded that NCA Li-ion batteries is around 3 times the environmental impact of LMO, putting them at the same level of NMC Li-ion batteries.

Therefore, NMC Li-ion batteries could be considered as the most pollutant Li-ion technology [216][219] but also the one that is generally used in most EV models. Thus, this study considers that NMC technology for environmental analysis is a good representative (and conservative option) of Li-ion batteries when compared with Li-S technology within an EV perspective.

This is exactly what *Deng et al.* did in their study, compared Li-S against NMC Li-ion batteries. Notice that they are the sole researchers that sought to perform an environmental impact

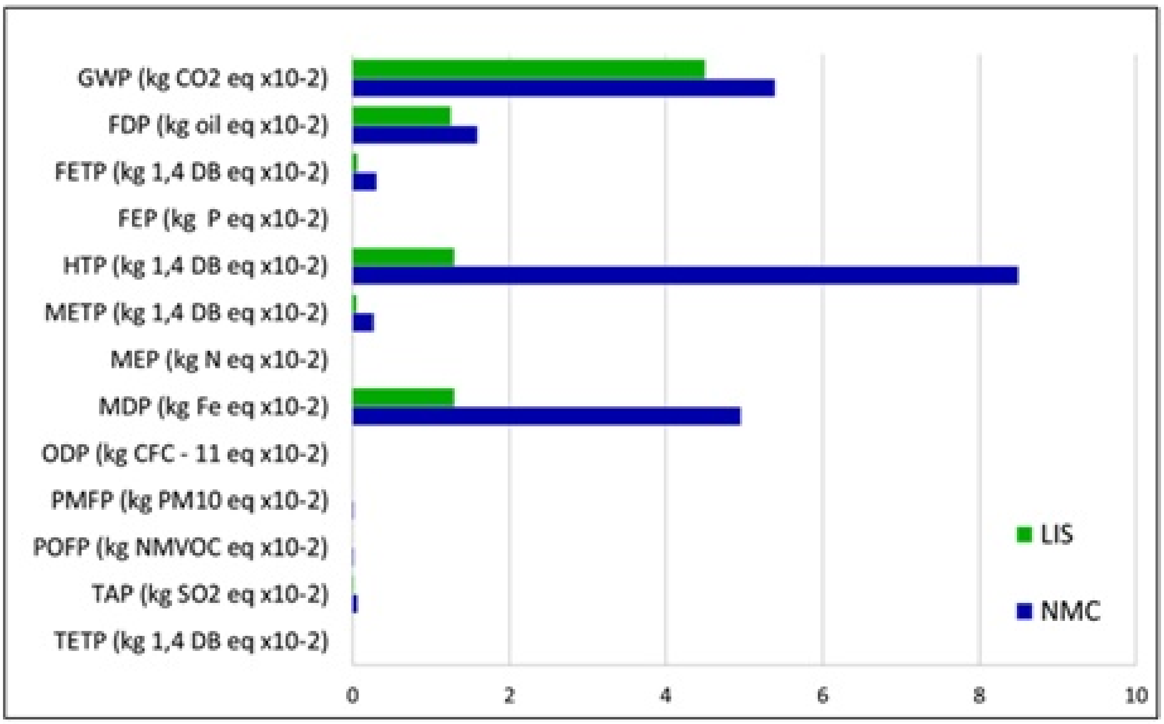

Figure 11.5: Life cycle impact benchmarking between the Li-S and the NCM-Graphite battery packs

analysis of Li-S [220]. Figure 11.5 presents their battery manufacturing results per category taking the same order of magnitude, including ReCiPe method for impact categories characterisation [221].

Figure 11.5 shows the results of the comparison of Li-S and NMC Li-ion batteries. More relevant differences are found in Human Toxicity Potential (HTP) impact category, where Li-S batteries obtain an 85% lower value, followed by Materials Depletion Potential (MDP) category, with a 74% reduction. GWP and Fossil Depletion Potential (FDP) resources have a lesser impact decrease around the 20%.

From this study, it can be ascertained that Li-S batteries have lower environmental impact results compared to NMC Li-ion. Firstly, Li-S batteries present a lower GWP (which is the category that better explains the impact of mankind in a globalized world) by a 20% in comparison to NMC Li-ion batteries, but its main contributions are found in huge reductions in resource depletion and human toxicity. Although results could be less favourable if Li-S batteries were compared to LFP or LMO batteries, these extreme reductions put them in a more favourable position. Moreover, we should consider that Li-S batteries are still in prototype and testing phases, which implies that there are still no industrialized manufacturing processes and, as a consequence, the uncertainty of the environmental analysis for Li-S is quite higher than the ones from Li-ion batteries.

Another aspect that should be highlighted with respect to Li-S batteries is the potential formation of H_2S and SO_2 gases in certain operation conditions, which is highly poisonous and leads to serious health complications and eventually death at concentrations above 1000ppm. This gas could be generated when Li-S cells achieve a temperature above 230 ºC (thermal runaway) [168]. *Donghai Liu et al.* have developed a new solution to transform H_2S and SO_2 gases into Water-dispersed Sulphur (WDS) nanoparticle which is contaminant-free. Both H_2S and SO_2 have high sulphur contents (94 wt% for H_2S and 50 wt% for SO_2). These two gases with an appropriate method can be converted into useful materials for a highly-efficient Li-S battery

[222]. Despite the encouraging results coming from this research, it is still unclear whether this can be applied to Li-S batteries for EVs. For this reason, though the formation of this gas is very unlikely, Li-S batteries casing should be capable of ensuring the proper sealing conditions to prevent this gas from leaking during tests or in operation phases.

In conclusion, from these initial studies, it can be stated that Li-S batteries present lower environmental impacts compared to Li-ion and there is still margin to improve once Li-S technology will become commercial and industrial scale manufactured.

11.2.4 Cost analysis

Literature emphasizes that one of the most important aspects of Li-S regarding Li-ion is its low cost [223][224][225][226]. For this reason, Table 11.3 presents a comparison of the cost per kilogram of the most relevant elements from different Li-ion and Li-S batteries. Notice that Table 11.3 considers the three Li-ion battery variants with higher practical specific energy (Wh/kg); Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Nickel Cobalt Aluminum Oxide (NCA). Consequently, the chemical elements presented are Cobalt, Nickel, Manganese, Aluminium and Sulphur.

Table 11.3: List of element prices of the analysed batteries. Unit value ($/t)

Year	**Lithium**	**Aluminium**	**Cobalt**	**Nickel**	**Manganese**	**Sulphur**
2000	4.470	1.640	29.700	8.640	582	24,7
2001	1.490	1.520	23.300	5.950	529	10
2002	1.590	1.430	17.100	6.770	471	11,8
2003	1.550	1.500	20.600	9.630	599	28,7
2004	1.720	1.850	43.400	13.800	1.090	32,6
2005	1.460	2.010	33.600	14.700	712	30,8
2006	2.320	2.680	30.700	24.200	800	32,9
2007	3.530	2.690	54.600	37.200	1.190	32,9
2008	4.440	2.660	68.400	21.100	2.380	264
2009	4.530	1.750	34.200	14.600	1.370	1,7
2010	4.350	2.300	39.700	21.800	1.500	70,2
2011	3.870	2.560	36.100	22.900	1.460	160
2012	4.220	2.230	30.500	17.500	1.400	124
2013	6.800	2.080	28.400	15.000	1.620	68,7
2014	6.690	2.300	31.900	16.900	1.350	80,1
2015	6.500	1.940	29.600	11.800	1.210	87,6
2016	8.650	1.800	26.400	9.500	1.780	37,88
2017	13.900	2.200	58.600	10.100	1.900	60
Average	**4.560**	**2.063**	**35.378**	**15.672**	**1.219**	**64**

Table 11.4: World production of the elements of the analysed batteries (tons)

Year	**Lithium**	**Aluminium**	**Cobalt**	**Nickel**	**Manganese**	**Sulphur**
2000	204.000	24.300.000	39.300	1.290.000	6.960.000	59.300.000
2015	604.000	57.500.000	126.000	2.280.000	17.500.000	68.900.000
Increase	**196%**	**137%**	**221%**	**77%**	**151%**	**16%**

Considering that the amount of materials needed for battery production is a small portion of the global demand, the variability of prices in Table 11.3 should not be attributed to the variations of battery production, it being hard to draw any logical correlation between prices. Regarding Sulphur, Table 11.3 shows how its price is much lower than all the other elements used in Li-ion batteries. Moreover, Table 11.4 presents how, except form Sulphur, all the elements doubled or tripled the world's demand.

In fact, the price of Sulphur is 32 times cheaper than Aluminium, 243 times cheaper than Nickel, 550 times cheaper than Cobalt and 20 times cheaper than Manganese. In order to confirm the Li-S battery price reduction in comparison to Li-ion, it is necessary to know their manufacturing costs. Unfortunately, Li-S batteries are still not commercialized, thus, this comparison cannot be performed. The development of large-scale, low-cost fabrication strategies for electrode materials with desirable performance represents an important challenge in the development of cost-effective Lithium/Sulphur cells [165]. Analysing prices in Table 11.3, it is appreciable that Lithium and Cobalt, which are the materials with higher prices, have a bull trend. Furthermore, Lithium and Cobalt according to [227], present a big uncertainty as a consequence of the dependence on the batteries with these materials. Even though the price of Sulphur does not follow any logical trend, their great availability and lower values position it within a certain advantage towards the actual Li-ion technology. *Isidor Buchmann* said that a price of US$250 per kWh of Li-S battery is possible [228], on the contrary, *Abbas Fotouhi et al.* prognosticate a more aggressive price (around $100 per kWh) [151].

Erik J. Berg et al. made a cost comparison between NMC (Li-ion) and Li-S batteries and the price difference of the cathode is considerable. The NMC cathode would have a cost of 33 $/kg when for Li-S would be 0,05 €/kg [229]. Note that the cost of the NMC cathode is 660 times greater, which reaffirms that our comparison between the elementary components of these batteries can be taken as correct.

11.3 Conclusions

After the analysis of the different key parameters required for EV applications, this chapter reports that Li-S are clearly ahead of Li-ion batteries in four of the analysed parameters. As shown in Table 11.5, these four key aspects are energy density, safety, price and environmental impact. On the contrary, Li-S batteries are rather less interesting in other important aspects such as lifecycle, self-discharge, power density and modelling.

Table 11.5: Summary table of the performance of the different Lithium chemicals

	Li-ion				**Li-S**
	NMC	NCA	LCO	LFP	
Energy density	+	+	+	+ −	+ + +
Power density	+ +	+ +	+ +	+	+ −
Lifecycle	+ +	+ −	+	+ +	− −
Self-discharge	+ +	+ +	+ +	+ +	− −
Safety	+	−	−	+ −	+
Price	−	+ −	+ −	+	+++
Model	+ +	+ +	+	+ −	−
Environmental	−	−	− −	+ −	+ +

Although both technologies (Li-S and Li-ion) can still improve their performances, Li-ion batteries are currently closer to their theoretical energy density limit than Li-S. This characteristic gives Li-S good perspectives and chances to be implemented in EVs in the nearby future. In addition, Li-S batteries are better qualified than Li-ion ones in safety (better), price (lower) and environmental impact (lower).

In fact, concerning the environmental aspects, Li-S preliminary results show that this technology has been far less harmful to humankind, reducing the GWP and the resource depletion than NMC Li-ion batteries, these results should be used carefully, as the manufacturing processes of Li-S batteries are not industrialized in contrast to those of Li-ion and they might change substantially.

Nonetheless, these four positive aspects are not enough for Li-S to substitute Li-ion batteries in EV applications. This chapter shows how the main drawbacks for Li-S concern durability, self-discharge and battery modelling. As it has been explained, Li-S chemical characteristics lead to undesired effects (such as shuttle and cathode expansion) that provoke low coulombic efficiency and short lifespan. Therefore, Li-S despite their high energy voltages compared to Li-ion, represent a challenge for EV applications.

Nowadays, Li-S battery modelling focus the attention on electrochemical models, to fully understand its behaviour, and are now making their first steps into ECN models, which are the ones preferred for EV applications.

In order to have real opportunities to substitute Li-ion, Li-S batteries should get closer to Li-ion on at least three parameters: durability, self-discharge and modelling. Knowing the potential and advantages of Li-S batteries, research should now focus attention on these three aspects rather than trying to improve the aspects that are already good enough.

Chapter 12

Conclusions and future work

> It is better to deserve honors and not have them than to have them and not to deserve them.
>
> Mark Twain.

This chapter concludes the PhD thesis, recapitulating the work conducted and providing the reader with an general overview of the author's results understanding. The most relevant findings obtained and thoroughly addressed in the previous chapters are briefly discussed here together with some final considerations regarding future possible opportunities in the connected fields.

12.1 Conclusions

The development of this dissertation should be understood as the result of the increasing interest of the automotive Original Equipment Manufacturers (OEMs) in the reuse of automotive batteries due to the recycling obligation they have together with the new business opportunities that are opening up around 2nd life batteries.

The project was supervised by Universitat Politècnica de Catalunya – BarcelonaTech (UPC) in collaboration with SEAT, the Spanish automaker. From the Electric Vehicle (EV) manufacturer point of view, if traction batteries confirm their suitability for a 2nd life, they could represent an additional source of revenue, which could lead to a reduction in the sales price of the EV. Moreover, the environmental footprint would be reduced since fewer batteries for energy storage would be manufactured, thus reducing both the consumption of the primary resources and the inherent waste.

By 2025 there will worldwide accumulative installed capacity of 2nd life batteries of 230 GWh and by 2030 the capacity will have increased over four times, achieving up to 1000 GWh, which presents huge opportunities for energy storage business [44].

Nevertheless, several economic, regulatory, and technical challenges still exist that the different companies should overcome it they want to profit from the 2nd life batteries business. The potential worth of 2nd life batteries is impacted by how the batteries are designed and used in their automotive life, how they are collected and used in 2nd life applications as well as the value of recycling. In consequence, this thesis conducts a depth analysis of key technologies, players, challenges and market opportunities over the 2nd life battery value chain in order to identify potential value opportunities.

First of all, in Chapter 6, an economic study of the battery disassembling is carried out. Depending on what type of application the battery will be reused, the level of disassembly to be reached will be determined.

The disassembling is performed in four different stages. At least, the first two are always performed. Removing the battery from the car and the post-auto battery assessment. Disassembly battery to modules and disassembly module to cells are only carried out if necessary.

The analysis made, ascertains that the reuse at battery level is the only economically viable option to reuse the batteries in another applications, as in a Stationary Energy Storage System (SESS). In contrast, the reuse of the complete battery pack brings with it major technological challenges, as the batteries maintain all the electronic management of the electric car and it is more difficult to integrate its functioning into the electrical ecosystem.

On the other hand, the reuse at module level introduces interesting advantages such as the potential to design more versatile and scalable solutions, which could have better market acceptance despite their initial higher cost.

Nowadays, the disassembling processes are very slow as a result of the wide variety of EV models and battery variants. This cost is expected to be reduced with the automation of processes and the bigger standardisation of batteries which could mean that finally the reuse at module level prevails in front of the complete battery pack.

Continuing on a disassembling business perspective, Chapter 7 compares the economic feasibility of setting up a battery treatment centre in Spain for dismantling the batteries, or otherwise, transporting them to Germany to be treated there.

Although only the logistical costs have been considered, the study reveals the average costs per year of transporting the batteries to Germany is 200% bigger than to transport them internally in Spain. In addition, if income generated by 2nd life batteries and recycling are considered, in the case of battery handling in Spain, positive income is generated from the first year, whereas, transporting them to Germany means that the break-even is not achieved until the third year. Moreover, the local scenario after 10 years generated 336% more profit.

Chapters 8 and 9 focused on the feasibility of installing a SESS from an economic and battery ageing point of view.

After analysing the Spanish legislative framework concerning the electricity network, based on a model previously developed by the UPC, in Chapter 8 a mathematical simulation model is developed capable of calculating the economic viability of installing a SESS in a real scenario taking into account the battery ageing. The model determines the savings that a SESS can generate in the electricity bill through the strategies of peak shaving and energy arbitrage. Electricity bill savings are calculated by comparing the annual expenses of the scenario with and without the presence of a SESS. To minimize investment and operational costs of the system, the model also optimizes the energy capacity of the SESS.

Following, 9 validates the simulation model through two real scenarios in Spain. In both cases, it can be seen how the installation of an SESS leads to significant savings in the electricity bill. These saving always are bigger using the energy arbitrage strategy. However, due to the battery ageing, in one scenario the Return of Investment (ROI) is positive, but in the other it is not. The viability of installing an SESS manufactured of 2nd life batteries strongly depends on its expected lifetime. Overall, results show that an appropriate ageing model combined with an economical study is required to determine the viability of installing a SESS.

In conclusion, besides the model and results obtained, this study proposes a methodology to calculate the feasibility of installing a SESS step by step.

Consequently, Chapter 10 aims at answering the question on whether a SESS made of 2nd life batteries can effectively work in a real scenario, in particular, in a home.

The experimental results show how the SESS can work integrated in the electricity network and charge the batteries directly from the Photovoltaics (PV) panels in order to minimize the electricity bill expenses. Moreover, the ROI calculation determines the economic feasibility of installing the SESS.

Finally Chapter 11 makes a comparison between Lithium-Sulphur and Lithium-Ion concerning the electro-mobility. Li-ion batteries are currently close to their theoretical energy density limit. Consequently, science has set about investigating chemical variants that may offer greater advantages. Now, it seems that the best placed to replace the Li-ion, is Lithium-Sulphur (Li-S).

Li-S batteries are clearly better than the current ones in energy density, safety, price and environmental impact. However, these batteries still have to improve a lot in aspects such as life-cycle, self-discharge, power density and modelling.

12.2 Future work

The conclusion of this project leaves space for further investigations in many of the related fields.

The future of second-life batteries is unclear and many issues concerning battery residual performances, rehabilitation costs, sustainable business models etc.. still need to be addressed.

Firstly, it could be interesting to improve the battery disassembling processes by evaluating more battery types and introducing automatic dismantling methods to optimise costs. On the other hand, as far as the battery processing centre is concerned, the study should be extended by considering aspects such as investment costs, layout of the centre and its location.

Secondly, the economic and ageing battery model should expand its framework in order to calculate the economic viability of installing a SESS in other countries. Moreover, new operating strategies can be implemented to expand the target customer. The new electricity grid regulation will also lead to an improvement in the method of calculation.

Lastly, other chemical variants such as Lithium-Air should given consideration.

Publications and conferences

This section provides the list of academic papers published as a result of this doctoral research, and also the list of the conferences and congresses in which we have participated.

Publications:

- **Comparison of the state of Lithium-Sulphur and lithium-ion batteries applied to electro-mobility**
  Authors: *G. Benveniste, H. Rallo, L. Canals Casals, A. Merino, B. Amante*
  DOI: 10.1016/j.jenvman.2018.08.008
  Published in: Journal of Environmental Management (Impact factor: 5,647)
- **Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases**
  Authors: *H. Rallo, L. Canals Casals, D. de la Torre, R. Reinhardt, C. Marchante, B. Amante*
  DOI: 10.1016/j.jclepro.2020.122584
  Published in: Journal of Cleaner Production (Impact factor: 7,246)
- **Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries**
  Authors: *H. Rallo, G. Benveniste, I. Gestoso, B. Amante*
  DOI: 10.1016/j.resconrec.2020.104785
  Published in: Resources, Conservation and Recycling (Impact factor: 8,086)

Conferences:

- A conference about the **"Actual state and new challenges of Li-Sulphur batteries for electrical vehicles"** was held during the *7th International Congress - Energy and Environment Engineering and Management* at Universidad de Las Palmas de Gran Canaria (Spain)
- A conference about **"Lithium-ion battery 2nd life used as an ESS: Ageing and Economic Analysis on different real scenarios"** was held during the *International Conference on Resource Sustainability - Cities (icRS Cities 2019)* at The University of Adelaide (Australia)
- A conference about the **"Economic and environmental analysis of the reuse of EV batteries"** was held during the *International Conference on Resource Sustainability - Cities (icRS Cities 2019)* at The University of Adelaide (Australia)

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Appendix

A Hourly distribution of electricity tariffs

```matlab
function [ TARIFA_6X, TARIFA_30A, TARIFA_31A, ...
    Peatge_Potencia_6X, Peatge_Potencia_30A, ...
    Peatge_Potencia_31A, Ki ] = Taules_Tarifaries (  )
%Hourly distribution of electricity tariffs
%   Load Energy and Power Tariff Tables (TTEP)
%
% Inputs:
%   n/a
%
% Outputs:
%   TARIFA_6X
%   TARIFA_30A
%   TARIFA_31A
%   Peatge_Potencia_6X
%   Peatge_Potencia_30A
%   Peatge_Potencia_31A
%   Ki
%

%% Tariff Tables

% Tariff Table 6.X
Hora        = (0:1:23)';
Gener       = {'P6','P6','P6','P6','P6','P6','P6','P6','P2','P2','P1','P1','P1','P2','P2','P2','P2','P2','P1','P1','P1','P2','P2','P2'}';
Febrer      = {'P6','P6','P6','P6','P6','P6','P6','P6','P2','P2','P1','P1','P1','P2','P2','P2','P2','P2','P1','P1','P1','P2','P2','P2'}';
Mars        = {'P6','P6','P6','P6','P6','P6','P6','P6','P4','P4','P4','P4','P4','P4','P4','P4','P3','P3','P3','P3','P3','P3','P4','P4'}';
Abril       = {'P6','P6','P6','P6','P6','P6','P6','P6','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5'}';
Maig        = {'P6','P6','P6','P6','P6','P6','P6','P6','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5'}';
Juny1       = {'P6','P6','P6','P6','P6','P6','P6','P6','P4','P3','P3','P3','P3','P3','P3','P4','P4','P4','P4','P4','P4','P4','P4','P4'}';
Juny2       = {'P6','P6','P6','P6','P6','P6','P6','P6','P2','P2','P2','P1','P1','P1','P1','P1','P1','P1','P1','P2','P2','P2','P2','P2'}';
Juliol      = {'P6','P6','P6','P6','P6','P6','P6','P6','P2','P2','P2','P1','P1','P1','P1','P1','P1','P1','P1','P2','P2','P2','P2','P2'}';
Agost       = {'P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6','P6'}';
Setembre    = {'P6','P6','P6','P6','P6','P6','P6','P6','P4','P3','P3','P3','P3','P3','P3','P4','P4','P4','P4','P4','P4','P4','P4','P4'}';
Octubre     = {'P6','P6','P6','P6','P6','P6','P6','P6','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5','P5'}';
Novembre    = {'P6','P6','P6','P6','P6','P6','P6','P6','P4','P4','P4','P4','P4','P4','P4','P4','P3','P3','P3','P3','P3','P3','P4','P4'}';
Desembre    = {'P6','P6','P6','P6','P6','P6','P6','P6','P2','P2','P1','P1','P1','P2','P2','P2','P2','P2','P1','P1','P1','P2','P2','P2'}';
TARIFA_6X   = table(Hora,Gener,Febrer,Mars,Abril,Maig,Juny1,Juny2,Juliol,Agost,Setembre,Octubre,Novembre,Desembre);

% Tariff Table 3.0A
Hora        = (0:23)';
Hivern      = {'P3','P3','P3','P3','P3','P3','P3','P3','P2','P2','P2','P2','P2','P2','P2','P2','P2','P2','P1','P1','P1','P1','P2','P2'}';
Estiu       = {'P3','P3','P3','P3','P3','P3','P3','P3','P2','P2','P2','P1','P1','P1','P1','P2','P2','P2','P2','P2','P2','P2','P2','P2'}';
TARIFA_30A  = table(Hora,Estiu,Hivern);

% Tariff Table 3.1A
Hora        = (0:23)';
Hivern      = {'P3','P3','P3','P3','P3','P3','P3','P3','P2','P2','P2','P2','P2','P2','P2','P2','P2','P1','P1','P1','P1','P1','P1','P2'}';
Estiu       = {'P3','P3','P3','P3','P3','P3','P3','P3','P2','P2','P1','P1','P1','P1','P1','P1','P2','P2','P2','P2','P2','P2','P2','P2'}';
CapDeSet    = {'P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P3','P2','P2','P2','P2','P2','P2'}';
TARIFA_31A  = table(Hora,Estiu,Hivern,CapDeSet);

%% Tables Term Power

% Cost Power Tariff 6.X
Peatge_Potencia_6X.P1 = 39.139427;
Peatge_Potencia_6X.P2 = 19.586654;
Peatge_Potencia_6X.P3 = 14.334178;
Peatge_Potencia_6X.P4 = 14.334178;
Peatge_Potencia_6X.P5 = 14.334178;
Peatge_Potencia_6X.P6 = 06.540177;

% Cost Power Tariff 3.0A
Peatge_Potencia_30A.P1 = 40.728885;
Peatge_Potencia_30A.P2 = 24.437330;
Peatge_Potencia_30A.P3 = 16.291555;

% Cost Power Tariff 3.1A
Peatge_Potencia_31A.P1 = 59.173468;
Peatge_Potencia_31A.P2 = 36.490689;
Peatge_Potencia_31A.P3 = 08.367731;
```

```

%% Excess Power Coefficient Table
Ki.P1 = 1;
Ki.P2 = 0.5;
Ki.P3 = 0.37;
Ki.P4 = 0.37;
Ki.P5 = 0.37;
Ki.P6 = 0.17;

end
```

B Public holidays

```
function [ dies_festius ] = Taula_Dies_Festius ( any_estudi )
%Taula_Dies_Festius
%   Returns list with the holidays of each year
%
% Inputs:
%   year_study: year in which the holidays are calculated
%
% Outputs:
%   holidays: array with holidays, in datetime format
%


% Fixed days (according to Spain calendar)
dies_festius = [...
    datetime(any_estudi,1,1),...
    datetime(any_estudi,1,6),...
    datetime(any_estudi,5,1),...
    datetime(any_estudi,8,15),...
    datetime(any_estudi,10,12),...
    datetime(any_estudi,11,1),...
    datetime(any_estudi,12,6),...
    datetime(any_estudi,12,8),...
    datetime(any_estudi,12,25)];

% Fixed days (according to Catalonia calendar)
% dies_festius = [dies_festius,...
%     datetime(any_estudi,6,24),...
%     datetime(any_estudi,9,11),...
%     datetime(any_estudi,12,26),...
%     ];

% Variable days:
% switch any_estudi
%     case 2015
%         dies_festius = [dies_festius,...
%             datetime(any_estudi,4,3),... % Holy Friday
%             ];
%     case 2016
%         dies_festius = [dies_festius,...
%             datetime(any_estudi,3,25),... % Holy Friday
%             ];
%     case 2017
%         dies_festius = [dies_festius,...
%             datetime(any_estudi,4,14),... % Holy Friday
%             datetime(any_estudi,4,17),... % Easter Monday
%             ];
%     case 2018
%         dies_festius = [dies_festius,...
%             datetime(any_estudi,3,30),... % Holy Friday
%             ];
% end

end
```

C Time change

```
function [ canvi_hora ] = Taula_Canvi_Hora ( any_estudi )
%Taula_Canvi_Hora
%   Returns the days of time change, expressed in local time
%
% Inputs:
%   year_study: year of study
%
% Outputs:
%   time_change: array with change days, in datetime format
%


% Selecciona any d'estudi
switch any_estudi
    case 2016
        canvi_hora(1) = datetime(2016,3,27,2,0,0);
        canvi_hora(2) = datetime(2016,10,30,3,0,0);
    case 2017
        canvi_hora(1) = datetime(2017,3,26,2,0,0);
```

```
        canvi_hora(2) = datetime(2017,10,29,3,0,0);
    case 2018
        canvi_hora(1) = datetime(2017,3,25,2,0,0);
        canvi_hora(2) = datetime(2017,10,28,3,0,0);
    otherwise % Not implemented
        error('Any %d no implementat!',any_estudi);
end

end
```

D Billing without battery

```
function [ total_facturacio ] = Facturacio_AGBAR ( ...
    arxiu_dades, tipus_dades, opts )
%Facturacio_AGBAR
%   Energy billing calculation
%
% Inputs:
%   data_file: archive of values separated by commas with the data
%   type: data file type (to determine how it is processed)
%   opts: structure with configuration options (optional)
%         Potencia_6X: table with the values of Contracted Power
%         odir: output directory where the results are saved
%         simulation_name: used as a prefix for result files
%         ploteja: shows graphs with the results of consumption of power
%         exporta_excel: exports the billing table in xlsx format
%         export_mat: exports the entire matlab workspace to a file
%         verbose: show processing information (1) or not (0)
%
% Outputs:
%   total_invoicing: total turnover during the period studied
%


%% Default input values

% Default data file
if nargin < 1 || isempty(arxiu_dades)
    arxiu_dades = fullfile('DATA','ComptadorGlobal_2017.csv');
end

% Default data file type
if nargin < 2 || isempty(tipus_dades)
    tipus_dades = 'Global';
end

% If the option variable (opts) is empty, we create it
if nargin < 3 || isempty(opts), opts.dummy = 1; end

% We check that all options are available
if ~isfield(opts,'odir'), opts.odir = fullfile('OUTPUT','DEFAULT'); end
if ~isfield(opts,'nom_simulacio'), opts.nom_simulacio = 'DEFAULT'; end
if ~isfield(opts,'plot_mensual'), opts.plot_mensual = 0; end
if ~isfield(opts,'plot_anual'), opts.plot_anual = 1; end
if ~isfield(opts,'exporta_excel'), opts.exporta_excel = 1; end
if ~isfield(opts,'exporta_mat'), opts.exporta_mat = 1; end
if ~isfield(opts,'verbose'), opts.verbose = 1; end
if ~isfield(opts,'valida'), opts.valida = 0; end
if ~isfield(opts,'debug'), opts.debug = 0; end

% Create output directory, if applicable
if ~exist(opts.odir,'dir'), mkdir(opts.odir); end

% Name of output files
nom_arxiu_T15 = fullfile(opts.odir,[opts.nom_simulacio,'.Taula_15']);
nom_arxiu_TFM = fullfile(opts.odir,[opts.nom_simulacio,'.Facturacio']);
nom_arxiu_mat = fullfile(opts.odir,[opts.nom_simulacio,'.Workspace.mat']);

%% We load Data

% Load Tariff Tables
[ TARIFA_6X, ~, ~, Peatge_Potencia_6X, ~, ~, Ki ] = Taules_Tarifaries();

% Load Energy Price Table
[ Preu_Energia_6X, ~ ] = Taules_Preu_Energia ( 2 );

% Load Contracted Power Table
if isfield(opts,'Potencia_Contractada_6X') % From data entry
    Potencia_Contractada_6X = opts.Potencia_Contractada_6X;
else % Load table by default
    [ Potencia_Contractada_6X, ~ ] = Taules_Potencia_Contractada();
end

% Upload CSV file with RAW data and convert it to a Table_15
Taula_15 = Genera_Taula_15 ( arxiu_dades, tipus_dades );

% Assume that the year of study is the same for the whole table
any_estudi = Taula_15.Data(1).Year;

% Load holiday table for the year of study
dies_festius = Taula_Dies_Festius ( any_estudi );

% We reorganize holidays by months (code optimization)
dies_festius_en_mes = cell(12,1);
```

```matlab
for mes_i=1:12
    diesf = dies_festius(dies_festius(:).Month==mes_i).Day;
    if isempty(diesf), dies_festius_en_mes{mes_i} = 0;
    else, dies_festius_en_mes{mes_i} = diesf;
    end
end

%% Information
if opts.verbose
    fprintf('Processant Facturaci\n');
    fprintf('Potencia Contractada: %.0f %.0f %.0f %.0f %.0f %.0f kW\n',...
        Potencia_Contractada_6X.P1,Potencia_Contractada_6X.P2,...
        Potencia_Contractada_6X.P3,Potencia_Contractada_6X.P4,...
        Potencia_Contractada_6X.P5,Potencia_Contractada_6X.P6);
end

%% We calculate billing for Energy (Quarterly)

% We upload the file if it is already simulated
if exist([nom_arxiu_T15,'.mat'],'file') % We upload mat file

    % Information
    if opts.verbose
        fprintf('Carregant valors de Facturacio Quarthoraris...\n');
    end

    % We load variable
    RAW = load([nom_arxiu_T15,'.mat']);
    Taula_15 = RAW.Taula_15;

else % Calculate Table_15 from 0

    % Information
    if opts.verbose
        fprintf('Calculant valors de Facturacio Quarthoraris...\n');
    end

    % We calculate billing by quarterly blocks
    Taula_15 = Calcula_Factura_Quarthorari ( Taula_15, TARIFA_6X, ...
        Preu_Energia_6X, Potencia_Contractada_6X, dies_festius_en_mes, ...
        opts.verbose );

    % Information
    if opts.verbose
        fprintf('Guardant arxius de resultats...\n');
    end

    % Save Table_15
    save([nom_arxiu_T15,'.mat'],'Taula_15');

    % Save Quarterly Table
    if opts.exporta_excel
        writetable(Taula_15,[nom_arxiu_T15,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',0);
    end

end

%% Generate Billing Table (Monthly)

% We upload the file if it is already simulated
if exist([nom_arxiu_TFM,'.mat'],'file') % We upload mat file

    % Information
    if opts.verbose
        fprintf('Carregant Taula de Facturacio Mensual...\n');
    end

    % Carreguem variable
    RAW = load([nom_arxiu_TFM,'.mat']);
    Taula_Facturacio_6X = RAW.Taula_Facturacio_6X;

else % Calculate Table_15 from 0

    % Information
    if opts.verbose
        fprintf('Generant Taula de Facturacio Mensual...\n');
    end

    % Generate billing table (empty)
    Taula_Facturacio_6X = Genera_Taula_Facturacio_6X();

    % Last month available at Taula_15
    ultim_mes = Taula_15.Data(end).Month;

    % We fill in the billing table
    for mes_i=1:ultim_mes % For each month of Table_15 ...

        % We calculate the bill for the month and add it to the billing table
        Taula_Facturacio_6X{:,mes_i} = Calcula_Factura_Mensual ( Taula_15, ...
            mes_i, Potencia_Contractada_6X, Peatge_Potencia_6X, Ki );

    end

    % Information
    if opts.verbose
        fprintf('Guardant arxius de resultats...\n');
    end

```

```
    % Save Table_15
    save([nom_arxiu_TFM,'.mat'],'Taula_Facturacio_6X');

    % Save Billing Table
    if opts.exporta_excel
        writetable(Taula_Facturacio_6X,[nom_arxiu_TFM,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',1);
    end

end

% Calculate the total turnover for the study year
total_facturacio = sum(Taula_Facturacio_6X{end,:});

% Calculate the error with the invoices (VALIDATION)
if opts.valida
    Error_Facturacio = Valida_Facturacio_2017 ( Taula_Facturacio_6X );
    disp('TAULA D''ERRORS D''ENERGIA CONSUMIDA RESPECTE A FACTURA (kWh)');
    disp('         Mes: [P1 P2 P3 P4 P5 P6 Total]');
    disp(Error_Facturacio); % Show billing error table
end

%% Export the workspace to matte, if necessary
if opts.exporta_mat

    % Information
    if opts.verbose
        fprintf('Exportant variables del workspace...\n');
    end

    % Save mat file
    save(nom_arxiu_mat);

end

%% Generate figures if necessary

% Plot anual
if opts.plot_anual

    % Information
    if opts.verbose
        fprintf('Generant grafiques anuals...\n');
    end

    % Draw annual graphs
    Facturacio_AGBAR_Plot ( 0, Taula_15, Taula_Facturacio_6X, opts );

end

% Plot mensual
if opts.plot_mensual

    % Information
    if opts.verbose
        fprintf('Generant grafiques mensuals...\n');
    end

    % Plot monthly charts
    for mes_i=1:ultim_mes
        Facturacio_AGBAR_Plot ( mes_i, Taula_15, ...
            Taula_Facturacio_6X, opts );
    end

end

%% Information
if opts.verbose
    fprintf('Facturacio: %s \euro\n',Sep1000Str(total_facturacio));
end

end
```

E Billing with battery

```
function [ total_facturacio_batt ] = Facturacio_AGBAR_BATT ( ...
    arxiu_dades, tipus_dades, tipus_llei_control, opts )
%Facturacio_AGBAR
%   Energy billing calculation
%
% Inputs:
%    data_file: comma-separated values file with AGBAR data
%    data_type: data file type (to determine how it is processed)
%    control_law type: battery control law type to apply
%    opts: structure with configuration options (optional)
%           Potencia_6X: table with the values of Contracted Power
%           odir: output directory where the results are saved
%           simulation_name: used as a prefix for result files
%           ploteja: shows graphs with the results of consumption of power
%           exporta_excel: exports the billing table in xlsx format
%           export_mat: exports the entire matlab workspace to a file
%           verbose: show processing information (1) or not (0)
%
% Outputs:
```

```matlab
%   total_invoicing: total turnover during the period studied
%


%% Default input values

% Default data file
if nargin < 1 || isempty(arxiu_dades)
    arxiu_dades = fullfile('DATA','ComptadorGlobal_2017.csv');
end

% Default data file type
if nargin < 2 || isempty(tipus_dades)
    tipus_dades = 'Global';
end

% Default control law type
if nargin < 3 || isempty(tipus_llei_control)
    tipus_llei_control = 'Compraventa';
end


% If the option variable (opts) is empty, we create it
if nargin < 4 || isempty(opts), opts.dummy = 1; end

% We check that all options are available
if ~isfield(opts,'odir'), opts.odir = fullfile('OUTPUT','DEFAULT_BATT'); end
if ~isfield(opts,'nom_simulacio'), opts.nom_simulacio = 'DEFAULT_BATT'; end
if ~isfield(opts,'plot_anual'), opts.plot_anual = 0; end
if ~isfield(opts,'plot_mensual'), opts.plot_mensual = 1; end
if ~isfield(opts,'exporta_excel'), opts.exporta_excel = 0; end
if ~isfield(opts,'exporta_mat'), opts.exporta_mat = 0; end
if ~isfield(opts,'verbose'), opts.verbose = 1; end
if ~isfield(opts,'valida'), opts.valida = 0; end
if ~isfield(opts,'debug'), opts.debug = 0; end

% Create output directory, if applicable
if ~exist(opts.odir,'dir'), mkdir(opts.odir); end

% Name of output files
nom_arxiu_T15 = fullfile(opts.odir,[opts.nom_simulacio,'.Taula_15']);
nom_arxiu_T15_BATT = fullfile(opts.odir,[opts.nom_simulacio,'.Taula_15_BATT']);
nom_arxiu_TFM = fullfile(opts.odir,[opts.nom_simulacio,'.Facturacio']);
nom_arxiu_TFM_BATT = fullfile(opts.odir,[opts.nom_simulacio,'.Facturacio_BATT']);
nom_arxiu_mat = fullfile(opts.odir,[opts.nom_simulacio,'.Workspace.mat']);

%% We load Data

% Load Tariff Tables
[ TARIFA_6X, ~, ~, Peatge_Potencia_6X, ~, ~, Ki ] = Taules_Tarifaries();

% Load Energy Price Table
[ Preu_Energia_6X, ~ ] = Taules_Preu_Energia ( 2 );

% Load Contracted Power Table
if isfield(opts,'Potencia_Contractada_6X') % From data entry
    Potencia_Contractada_6X = opts.Potencia_Contractada_6X;
else % Load table by default
    [ Potencia_Contractada_6X, ~ ] = Taules_Potencia_Contractada();
end

% Upload CSV file with RAW data and convert it to a Table_15
Taula_15 = Genera_Taula_15 ( arxiu_dades, tipus_dades );

% Assume that the year of study is the same for the whole table
any_estudi = Taula_15.Data(1).Year;

% Load holiday table for the year of study
dies_festius = Taula_Dies_Festius ( any_estudi );

% We reorganize holidays by months (code optimization)
dies_festius_en_mes = cell(12,1);
for mes_i=1:12
    diesf = dies_festius(dies_festius(:).Month==mes_i).Day;
    if isempty(diesf), dies_festius_en_mes{mes_i} = 0;
    else, dies_festius_en_mes{mes_i} = diesf;
    end
end

% We load Battery Settings
[ BATT ] = Parametres_BATT ( );

%% Information
if opts.verbose
    fprintf('Processant Facturacio n');
    fprintf('Potencia Contractada: %.0f %.0f %.0f %.0f %.0f %.0f kW\n',...
        Potencia_Contractada_6X.P1,Potencia_Contractada_6X.P2,...
        Potencia_Contractada_6X.P3,Potencia_Contractada_6X.P4,...
        Potencia_Contractada_6X.P5,Potencia_Contractada_6X.P6);
end

%% We calculate billing for Energy (Quarterly)

% We upload the file if it is already simulated
if exist([nom_arxiu_T15,'.mat'],'file') % We upload mat file

    % Information
    if opts.verbose
        fprintf('Carregant valors de Facturacio Quarthoraris...\n');
```

```
    end

    % We load variable
    RAW = load([nom_arxiu_T15,'.mat']);
    Taula_15 = RAW.Taula_15;

else % Calculate Table_15 from 0

    % Information
    if opts.verbose
        fprintf('Calculant valors de Facturacio Quarthoraris...\n');
    end

    % We calculate billing by quarterly blocks
    Taula_15 = Calcula_Factura_Quarthorari ( Taula_15, TARIFA_6X, ...
        Preu_Energia_6X, Potencia_Contractada_6X, dies_festius_en_mes, ...
        opts.verbose );

    % Information
    if opts.verbose
        fprintf('Guardant arxius de resultats...\n');
    end

    % Save Table_15
    save([nom_arxiu_T15,'.mat'],'Taula_15');

    % Save Quarterly Table
    if opts.exporta_excel
        writetable(Taula_15,[nom_arxiu_T15,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',0);
    end

end

%% Re-Calculate Billing for Energy + BATT (Quarter Hours)

% We upload the file if it is already simulated
if exist([nom_arxiu_T15_BATT,'.mat'],'file') % We upload mat file

    % Information
    if opts.verbose
        fprintf('Carregant valors de Facturacio Quarthoraris (BATT)...\n');
    end

    % We load variable
    RAW = load([nom_arxiu_T15_BATT,'.mat']);
    Taula_15_BATT = RAW.Taula_15_BATT;

else % Calculate Table_15 from 0

    % Information
    if opts.verbose
        fprintf('Aplicant bateries...\n');
    end

    % We recalculate Power / Energy values consumed by applying batteries
    Taula_15_BATT = Calcula_Taula_15_BATT ( Taula_15, BATT, ...
        tipus_llei_control, opts.verbose );

    % Information
    if opts.verbose
        fprintf('Calculant valors de Facturacio Quarthoraris (BATT)...\n');
    end

    % We calculate billing by quarterly blocks
    Taula_15_BATT = Calcula_Factura_Quarthorari ( Taula_15_BATT, ...
        TARIFA_6X, Preu_Energia_6X, Potencia_Contractada_6X, ...
        dies_festius_en_mes, opts.verbose );

    % Information
    if opts.verbose
        fprintf('Guardant arxius de resultats...\n');
    end

    % Save Table_15
    save([nom_arxiu_T15_BATT,'.mat'],'Taula_15_BATT');

    % Save Quarterly Table
    if opts.exporta_excel
        writetable(Taula_15_BATT,[nom_arxiu_T15_BATT,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',0);
    end

end

%% Generate Billing Table (Monthly)

% We upload the file if it is already simulated
if exist([nom_arxiu_TFM,'.mat'],'file') % We upload mat file

    % Information
    if opts.verbose
        fprintf('Carregant Taula de Facturacio Mensual...\n');
    end

    % We load variable
    RAW = load([nom_arxiu_TFM,'.mat']);
    Taula_Facturacio_6X = RAW.Taula_Facturacio_6X;

```

```
    % Variable load (BATT)
    RAW = load([nom_arxiu_TFM_BATT,'.mat']);
    Taula_Facturacio_6X_BATT = RAW.Taula_Facturacio_6X_BATT;

else % Calculate Table_15 from 0

    % Information
    if opts.verbose
        fprintf('Generant Taula de Facturacio...\n');
    end

    % Generate billing table (empty)
    [ Taula_Facturacio_6X ] = Genera_Taula_Facturacio_6X(); % No battery
    [ Taula_Facturacio_6X_BATT ] = Genera_Taula_Facturacio_6X(); % With battery

    % Last month available at Taula_15
    ultim_mes = Taula_15.Data(end).Month;

    % We fill in the billing table
    for mes_i=1:ultim_mes % For each month of Table_15 ...

        % No Battery
        % We calculate the bill for the month and add it to the billing table
        Taula_Facturacio_6X{:,mes_i} = Calcula_Factura_Mensual ( ...
            Taula_15, mes_i, Potencia_Contractada_6X, ...
            Peatge_Potencia_6X, Ki );

        % With Battery
        % We calculate the bill for the month and add it to the billing table
        Taula_Facturacio_6X_BATT{:,mes_i} = Calcula_Factura_Mensual ( ...
            Taula_15_BATT, mes_i, Potencia_Contractada_6X, ...
            Peatge_Potencia_6X, Ki );

    end

    % Information
    if opts.verbose
        fprintf('Guardant arxius de resultats...\n');
    end

    % Save Table_15
    save([nom_arxiu_TFM,'.mat'],'Taula_Facturacio_6X');
    save([nom_arxiu_TFM_BATT,'.mat'],'Taula_Facturacio_6X_BATT');

    % Save Billing Table
    if opts.exporta_excel
        writetable(Taula_Facturacio_6X,[nom_arxiu_TFM,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',1);
        writetable(Taula_Facturacio_6X_BATT,[nom_arxiu_TFM_BATT,'.xlsx'],...
            'WriteVariableNames',1,'WriteRowNames',1);
    end

end

% Calculate the total turnover for the study year
total_facturacio_batt = sum(Taula_Facturacio_6X_BATT{end,:});

% Calculate the error with the invoices (VALIDATION)
if opts.valida
    Error_Facturacio = Valida_Facturacio_2017 ( Taula_Facturacio_6X );
    disp('TAULA D''ERRORS D''ENERGIA CONSUMIDA RESPECTE A FACTURA (kWh)');
    disp('         Mes: [P1 P2 P3 P4 P5 P6 Total]');
    disp(Error_Facturacio); % Show billing error table
end

%% Export the workspace to matte, if necessary
if opts.exporta_mat

    % Information
    if opts.verbose
        fprintf('Exportant variables del workspace...\n');
    end

    % Guarda arxiu mat
    save(nom_arxiu_mat);

end

%% Generate figures if necessary

% Plot anual
if opts.plot_anual

    % Information
    if opts.verbose
        fprintf('Generant grafiques anuals...\n');
    end

    % Draws annual graphs
    Plot_Consums ( 0, Taula_15, Taula_Facturacio_6X, opts );
    Plot_Consums ( 0, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );
    Plot_Facturacio ( 0, Taula_15, Taula_Facturacio_6X, opts );
    Plot_Facturacio ( 0, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );
    Plot_Bateries ( 0, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );

end

% Plot mensual
if opts.plot_mensual
```

```

    % Information
    if opts.verbose
        fprintf('Generant grafiques mensuals...\n');
    end

    % Plot monthly charts
    for mes_i=1:Taula_15.Data(end).Month
        Plot_Consums ( mes_i, Taula_15, Taula_Facturacio_6X, opts );
        Plot_Consums ( mes_i, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );
        Plot_Facturacio ( mes_i, Taula_15, Taula_Facturacio_6X, opts );
        Plot_Facturacio ( mes_i, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );
        Plot_Bateries ( mes_i, Taula_15_BATT, Taula_Facturacio_6X_BATT, opts, 'BATT' );
    end

end

%% Information
if opts.verbose
    fprintf('Facturacio: %s euro\n',Sep1000Str(total_facturacio_batt));
end

end
```

F Battery parameters

```
function [ BATT ] = Parametres_BATT ( ID )
%Parametres_BATT
%   Returns the battery object settings for billing
%
% Inputs:
%   ID: Battery identifier
%
% Outputs:
%   BATT: structure with the properties of the battery. Details in the code.
%


% Default battery ID
if nargin < 1 || isempty(ID), ID = 1; end

% We select battery
switch ID
    case 1
        BATT.nom = 'Batt1';
        BATT.potencia = 2000; % [kW]
        BATT.capacitat = 10000; % [kWh]
        BATT.carrega_minima = 0.15 * BATT.capacitat; % [kWh]
        BATT.carrega_maxima = 0.95 * BATT.capacitat; % [kWh]
        BATT.estat_de_carrega_actual = 0; % [kWh]
        BATT.C_carrega = 0; % [-]
        BATT.C_descarrega = 0; % [-]
        BATT.estat = 'parada';

    case 2
        BATT.nom = 'Batt2';

    case 3
        BATT.nom = 'Batt3';

    otherwise
        error('Bateria %d no implementada',ID);
end

end
```

G Energy price tables

```
function [ Preu_Energia_6X, Preu_Energia_31A ] = ...
    Taules_Preu_Energia ( versio )
% Energy_Price_Tables
%   Energy Price Tables
%
% Inputs:
%
%
% Outputs:
%   Preu_Energia_6X
%   Preu_Energia_31A
%


% Tariff Table 6.X
switch versio
    case 1
        Preu_Energia_6X.P1 = 0.1003047;
        Preu_Energia_6X.P2 = 0.0883471;
        Preu_Energia_6X.P3 = 0.0785100;
```

```
        Preu_Energia_6X.P4 = 0.0707174;
        Preu_Energia_6X.P5 = 0.0663992;
        Preu_Energia_6X.P6 = 0.0527767;
    case 2
        Preu_Energia_6X.P1 = 0.099357;
        Preu_Energia_6X.P2 = 0.086877;
        Preu_Energia_6X.P3 = 0.077248;
        Preu_Energia_6X.P4 = 0.067167;
        Preu_Energia_6X.P5 = 0.062156;
        Preu_Energia_6X.P6 = 0.050197;
end

% Tariff Table 3.1A
Preu_Energia_31A.P1 = 0.085488;
Preu_Energia_31A.P2 = 0.077495;
Preu_Energia_31A.P3 = 0.058124;

end
```

H Energy Arbitrage

```
function [ BATT, estat, flux_energia ] = Llei_Control_Compraventa ( ...
    BATT, periodes_dia_unique, Px, potencia_disponible )
%Law_Control_Red_Simple_01
%   Battery performance control law
%
% The battery is charged during the cheapest period of the day
% The battery is discharged during the most expensive period of the day
% Upload / download is only performed if possible
%
% Inputs:
%  BATT: current battery settings
%  periodes_dia_unique: array with the billing periods of the day
%  Px: Current billing period
%  available_power: power available under contract
%
% Outputs:
%  BATT: Updated battery settings
%  status: battery activity (charging, discharging, resting)
%  power_flow: energy charged / discharged to / from the battery
%      loaded: power_flow> 0
%      downloaded: energy_flow <0
%      at rest: energy_flow = 0
%


% More expensive and cheaper period
periode_car = periodes_dia_unique{1};
periode_barat = periodes_dia_unique{end};

% What is left of the load to reach the maximum load
carrega_fins_al_maxim = BATT.carrega_maxima - BATT.estat_de_carrega_actual;

% What is left of the load to reach the minimum load
carrega_fins_al_minim = BATT.estat_de_carrega_actual - BATT.carrega_minima;

% What is charging / discharging a battery in a block of 15 minutes
delta_carrega = min([potencia_disponible,BATT.potencia]) * 15/60; % [kWh]
delta_descarrega = BATT.potencia * 15/60; % [kWh]

% Law of battery performance
if strcmpi(Px,periode_barat) % If we are in the cheapest period, we charge battery

    % We check that we can charge the battery
    if BATT.estat_de_carrega_actual < BATT.carrega_maxima && ... % We are below the maximum
            delta_carrega < carrega_fins_al_maxim % We will not exceed the maximum in this 15-minute block
        estat = 'carregant';
        flux_energia = delta_carrega;
    elseif carrega_fins_al_maxim > 0 % We can still charge the battery
        estat = 'carregant';
        flux_energia = carrega_fins_al_maxim;
    else % Battery is already charged
        estat = 'repos';
        flux_energia = 0;
    end

elseif strcmpi(Px,periode_car) % If we are in the most expensive period, we discharge battery

    % We check that we can download
    if BATT.estat_de_carrega_actual > BATT.carrega_minima && ... % We are above the minimum
        delta_descarrega < carrega_fins_al_minim % We will not exceed the minimum unloading
        estat = 'descarregant';
        flux_energia = - delta_descarrega;
    elseif carrega_fins_al_minim > 0 % There is still energy to download
        estat = 'descarregant';
        flux_energia = - carrega_fins_al_minim;
    else % Battery is already discharged, or we would discharge below the minimum
        estat = 'repos';
        flux_energia = 0;
    end

else % In any other period...
    estat = 'repos';
    flux_energia = 0;
```

```
end

% We recalculate current battery charge status
BATT.estat_de_carrega_actual = BATT.estat_de_carrega_actual + flux_energia;

% We update current battery status
BATT.estat = estat;

end
```

I Peak Shaving

```
function [ BATT, estat, flux_energia ] = Llei_Control_PeakShaving ( ...
    BATT, periodes_dia_unique, Px, potencia_disponible, ...
    idx_Px_ordenats_batt, idx, verbose )
%Llei_Control_PeakSaving
%   Battery performance control law
%
% The battery is charged during the cheapest period of the day
% The battery is discharged when there is excess power, from higher
% power in expensive period, until lower power in cheap period.
% Upload / download is only performed if possible
%
% Inputs:
%    BATT: Current battery settings
%    periodes_dia_unique: array with the billing periods of the day
%    Px: Current billing period
%    available_power: power available under contract
%    idx_Px_ordered_bat: indexes of the peaks, sorted descending by Px
%    idx: current index
%
% Outputs:
%     BATT: Updated battery settings
%     status: battery activity (charging, discharging, resting)
%     power_flow: energy charged / discharged to / from the battery
%          loaded: power_flow> 0
%          downloaded: energy_flow <0
%          at rest: energy_flow = 0
%


% Are we at a peak to absorb?
must_shave_peak = ismember(idx,idx_Px_ordenats_batt);

if must_shave_peak && verbose
    disp(' Shaving peak!');
end

% More expensive and cheaper period
periode_barat = periodes_dia_unique{end};

% What is left of the load to reach the maximum load
carrega_fins_al_maxim = BATT.carrega_maxima - BATT.estat_de_carrega_actual;

% What is left of the load to reach the minimum load
carrega_fins_al_minim = BATT.estat_de_carrega_actual - BATT.carrega_minima;

% What is charging / discharging a battery in a block of 15 minutes
delta_carrega = min([potencia_disponible,BATT.potencia]) * 15/60; % [kWh]
delta_descarrega = BATT.potencia * 15/60; % [kWh]

% Law of battery performance
if strcmpi(Px,periode_barat) % If we are in the cheapest period, we charge battery

    % We check that we can load
    if BATT.estat_de_carrega_actual < BATT.carrega_maxima && ... % We are below the maximum
            delta_carrega < carrega_fins_al_maxim % We will not exceed the maximum in this 15-minute block
        estat = 'carregant';
        flux_energia = delta_carrega;
    elseif carrega_fins_al_maxim > 0 % We can still charge the battery
        estat = 'carregant';
        flux_energia = carrega_fins_al_maxim;
    else % Battery is already charged
        estat = 'repos';
        flux_energia = 0;
    end

elseif must_shave_peak % If we need to remove peak, we discharge battery

    % We check that we can download
    if BATT.estat_de_carrega_actual > BATT.carrega_minima && ... % We are above the minimum
        delta_descarrega < carrega_fins_al_minim % We will not exceed the minimum discharging
        estat = 'descarregant';
        flux_energia = - delta_descarrega;
    elseif carrega_fins_al_minim > 0 % There is still energy to download
        estat = 'descarregant';
        flux_energia = - carrega_fins_al_minim;
    else % Battery is already discharged, or we would discharge below the minimum
        estat = 'repos';
        flux_energia = 0;
    end

else % In any other period ...
    estat = 'repos';
```

```
    flux_energia = 0;
end

% We recalculate current battery charge status
BATT.estat_de_carrega_actual = BATT.estat_de_carrega_actual + flux_energia;

% We update current battery status
BATT.estat = estat;

end
```

J Calculate monthly bill

```
function [ factura_mes ] = Calcula_Factura_Mensual ( Taula_15, mes_i, ...
    Potencia_Contractada_6X, Peatge_Potencia_6X, Ki )
%Generate_Monthly_Invoice
%   Calcula els valors de facturacio mensuals
%
% Inputs:
%   Taula_15
%   mes_i
%   facturacio_energia
%   registre_exces_potencia
%   periodes
%   Potencia_Contractada_6X
%   Peatge_Potencia_6X
%   Ki
%
% Outputs:
%   invoice_month: array with billing values, according to the 6X billing table
%


% We select all the elements in table15 that correspond to the current month
indexos_mes = Taula_15.Data.Month == mes_i;

% Energy consumption for the current month
consum_energia_mes = Taula_15.Energia(indexos_mes);

% Energy billing for the current month
facturacio_energia_mes = Taula_15.Facturacio_energia(indexos_mes);

% Excess Power of the current month
registre_exces_mes = Taula_15.Registre_exces_potencia(indexos_mes);

% Periods of the current month
periodes_mes = Taula_15.Periode(indexos_mes);

% Compute the subtotals for each period
consum_energia_Px = zeros(6,1);
facturacio_energia_Px = zeros(6,1);
facturacio_potencia_Px = zeros(6,1);
facturacio_exces_Px = zeros(6,1);
for p=1:6 % For each of the 6 periods (P1, P2, ...)

    % Current period Px (in string format)
    Px = sprintf('P%d',p);

    % We look for the indices of the month that correspond to the period Px
    indexos_Px = ismember(periodes_mes,Px);

    % We add all the values of the month that correspond to the period Px
    consum_energia_Px(p) = sum(consum_energia_mes(indexos_Px));
    facturacio_energia_Px(p) = sum(facturacio_energia_mes(indexos_Px));
    facturacio_potencia_Px(p) = Potencia_Contractada_6X.(Px) ...
        * Peatge_Potencia_6X.(Px) / 12;

    % We calculate excess power
    excessos_Px = registre_exces_mes(indexos_Px);
    Aei = sqrt(sum(excessos_Px.^2));
    facturacio_exces_Px(p) = Ki.(Px) * (234/166.386) * Aei;

end

% We calculate subtotals and totals
consum_energia_total = sum(consum_energia_Px);
facturacio_energia_total = sum(facturacio_energia_Px);
facturacio_potencia_total = sum(facturacio_potencia_Px);
facturacio_exces_total = sum(facturacio_exces_Px);
facturacio_subtotal = facturacio_energia_total ...
    + facturacio_potencia_total + facturacio_exces_total;
impost_electric = facturacio_subtotal * 0.05112696;
impost_lloguer_comptador = 99;
iva = (facturacio_subtotal + impost_electric ...
    + impost_lloguer_comptador) * 0.21;
total_factura = facturacio_subtotal + impost_electric ...
    + impost_lloguer_comptador + iva;

% We build the vector to add to the Billing_Table_6X
factura_mes = [...
    facturacio_energia_Px(:);...
    facturacio_energia_total;...
    consum_energia_Px(:);...
    consum_energia_total;...
```

```
    facturacio_potencia_Px;...
    facturacio_potencia_total;...
    facturacio_exces_Px(:);...
    facturacio_exces_total;...
    facturacio_subtotal;...
    impost_electric;...
    impost_lloguer_comptador;...
    iva;...
    total_factura];

end
```

K Calculate quarterly invoice

```
function [ Taula_15 ] = Calcula_Factura_Quarthorari ( Taula_15, TARIFA_6X, ...
    Preu_Energia_6X, Potencia_Contractada_6X, dies_festius_en_mes, ...
    verbose )
%Calcula_Factura_Quarthorari
%   Calculate billing by quarterly blocks
%

% We precalculate table length
lt = length(Taula_15.Potencia);

% We initialize variables of interest
periodes_any = cell(lt,1);
potencia_contractada = zeros(lt,1);
registre_exces_potencia = zeros(lt,1);
facturacio_energia = zeros(lt,1);

% For each quarterly block (15min) of the table ...
for i=1:lt

    % We save data from the table corresponding to the current block
    data_i = Taula_15.Data_Local(i); % Date in Local Time
    potencia_consumida_i = Taula_15.Potencia(i); % Power consumed [kW]
    energia_consumida_i = Taula_15.Energia(i); % Energy consumed [kWh]

    % Info
    if(mod(i,360)==0) && verbose % Show info every 360 blocks
        fprintf(' Bloc %d/%d (%.0f%%)\n',i,lt,i/lt*100);
    end

    % Calculate billing period
    Px = Calcula_Periode_Px ( '6.1', TARIFA_6X, ...
        data_i, dies_festius_en_mes );

    % What power do we have contracted in this period?
    potencia_contractada_i = Potencia_Contractada_6X.(Px);

    % What excess power do we have in this period?
    % We will only calculate excesses when the power consumed is greater than the contracted power
    if potencia_consumida_i > potencia_contractada_i
        exces_potencia = potencia_consumida_i - potencia_contractada_i;
    else
        exces_potencia = 0;
    end

    % Save variables of interest
    periodes_any{i} = Px; % Period (P1, P2, ...)
    potencia_contractada(i) = potencia_contractada_i; % Contracted power
    registre_exces_potencia(i) = exces_potencia; % Excess power
    facturacio_energia(i) = Preu_Energia_6X.(Px) * energia_consumida_i; % Energy

end

% We save variables of interest in Table_15
Taula_15.Periode = periodes_any;
Taula_15.Potencia_contractada = potencia_contractada;
Taula_15.Registre_exces_potencia = registre_exces_potencia;
Taula_15.Facturacio_energia = facturacio_energia;

end
```

L Calculate period Px

```
function [ Px ] = Calcula_Periode_Px ( tipus_facturacio, TARIFA_6X, ...
    data_i, dies_festius_en_mes )
%Calcula_Periode_Px
%   Determina el periode de facturacio (6.1, 3.0A, 3.1A, etc.)
%


% Seleccionem tipus de facturacio
switch tipus_facturacio

    case '6.1' % Billing for 6 periods (6.1)

```

```
        % We save data from the table corresponding to the current block
        mes_i = data_i.Month; % Current month
        dia_i = data_i.Day; % Day of the month
        hora_i = data_i.Hour; % Current time

        % What month are we in?
        switch mes_i
            case 1, mes_actual = 'Gener';
            case 2, mes_actual = 'Febrer';
            case 3, mes_actual = 'Mars';
            case 4, mes_actual = 'Abril';
            case 5, mes_actual = 'Maig';
            case 6 % June (2 sub-periods!)
                if dia_i<16, mes_actual = 'Juny1';
                else, mes_actual = 'Juny2';
                end
            case 7, mes_actual = 'Juliol';
            case 8, mes_actual = 'Agost';
            case 9, mes_actual = 'Setembre';
            case 10, mes_actual = 'Octubre';
            case 11, mes_actual = 'Novembre';
            case 12, mes_actual = 'Desembre';
        end

        % Day of the week (Saturday == 7, Sunday == 1)
        dia_setmana = weekday(data_i); % Identify the day of the week
        es_finde = ismember(dia_setmana,[7,1]); % Is it Saturday / Sunday?

        % Check if the current day is a public holiday
        es_festa = ismember(dia_i,dies_festius_en_mes{mes_i});

        % Let's see what period we are in (P1, P2, ...)
        if es_finde || es_festa % We assign P6 on holidays / weekends
            Px = 'P6';
        else % We look for the period with the Tariff Distribution Table
            Px = TARIFA_6X.(mes_actual){hora_i+1};
        end

    case '3.0A'

    case '3.1A'

    otherwise


end
```

M Generate table 15

```
function [ Taula_15 ] = Genera_Taula_15 ( arxiu_dades, tipus_dades )
%Genera_Taula_15
%   Upload CSV file with RAW data and generate a quarterly table
%
% Inputs:
%     data_file: path to CSV file with data in RAW
%     data_type: file type, to discriminate the format of the data
%
% Outputs:
%     Table_15: table with UTC date, local date, power consumed and
%               power consumed, in blocks of 15 minutes (quarterly)
%


% Upload CSV file with RAW data and convert it to a Table_15
switch tipus_dades
    case 'Global' % Global data
        Taula_15 = Genera_Taula_15_Desde_Quarthorari ( arxiu_dades );
    case 'PRET' % Pretreatment Data
        Taula_15 = Genera_Taula_15_Desde_Minutal ( ...
            arxiu_dades,{'dd-MM-yyyy','HH:mm:ss'} );
    case 'BINT' % Intermediate Pumping Data
        Taula_15 = Genera_Taula_15_Desde_Minutal ( ...
            arxiu_dades,{'dd/MM/yyyy','HH:mm'} );
    case 'TERC' % Tertiary Process Data
        Taula_15 = Genera_Taula_15_Desde_Minutal ( ...
            arxiu_dades,{'dd/MM/yyyy','HH:mm'} );
    otherwise
        error('TIPUS DE DADES "%s" NO IMPLEMENTAT',tipus);
end

% Assume that the year of study is the same for the whole table
any_estudi = Taula_15.Data(1).Year;

% Add column to Table_15 with date in local time
canvi_hora = Taula_Canvi_Hora ( any_estudi ); % Days of time change
Taula_15.Data_Local = Taula_15.Data; % Create a new local time column
hora_hivern = Taula_15.Data_Local <= canvi_hora(1); % Winter schedule
Taula_15.Data_Local(hora_hivern).Hour = Taula_15.Data_Local(hora_hivern).Hour + 1;
hora_estiu = Taula_15.Data_Local > canvi_hora(1); % Summer time
Taula_15.Data_Local(hora_estiu).Hour = Taula_15.Data_Local(hora_estiu).Hour + 1;
hora_hivern2 = Taula_15.Data_Local >= canvi_hora(2); % Winter schedule
Taula_15.Data_Local(hora_hivern2).Hour = Taula_15.Data_Local(hora_hivern2).Hour - 1;

end
```

```matlab

function [ Taula_15 ] = Genera_Taula_15_Desde_Quarthorari ( ...
    filename, startRow, endRow )
% Load_Table_15
%      Loads a Table_15 from data in csv file
%      The data in the csv file must be in quarterly blocks
%
%   File generated by Matlab


% Initialize variables.
delimiter = ';';
if nargin<=2
    startRow = 2;
    endRow = inf;
end

% Format for each line of text:
%   column1: datetimes (%{dd/MM/yyyy HH:mm}D)
%   column2: double (%f)
%   column3: double (%f)
% For more information, see the TEXTSCAN documentation.
formatSpec = '%{dd/MM/yyyy HH:mm}D%f%f%[^\n\r]';

% Open the text file.
fileID = fopen(filename,'r');

% Read columns of data according to the format.
% This call is based on the structure of the file used to generate this
% code. If an error occurs for a different file, try regenerating the code
% from the Import Tool.
dataArray = textscan(fileID, formatSpec, endRow(1)-startRow(1)+1, ...
    'Delimiter', delimiter, 'TextType', 'string', 'EmptyValue', NaN, ...
    'HeaderLines', startRow(1)-1, 'ReturnOnError', false, ...
    'EndOfLine', '\r\n');
for block=2:length(startRow)
    frewind(fileID);
    dataArrayBlock = textscan(fileID, formatSpec, ...
        endRow(block)-startRow(block)+1, 'Delimiter', delimiter, ...
        'TextType', 'string', 'EmptyValue', NaN, 'HeaderLines', ...
        startRow(block)-1, 'ReturnOnError', false, 'EndOfLine', '\r\n');
    for col=1:length(dataArray)
        dataArray{col} = [dataArray{col};dataArrayBlock{col}];
    end
end

% Close the text file.
fclose(fileID);

% Create output variable
Taula_15 = table(dataArray{1:end-1}, 'VariableNames', ...
    {'Data','Energia','Potencia'});

end

function [ Taula_15 ] = Genera_Taula_15_Desde_Minutal ( ...
    nom_fitxer_csv, dateFormats )
% Load_Table_15_From_Minutal
%   Distribute the data in blocks of 15 rows and sum

% Mat data file name
[~,nom_csv,~] = fileparts(nom_fitxer_csv);
nom_arxiu_mat = fullfile('DATA',[nom_csv,'.mat']);

% If the file is already processed, upload and return it
if exist(nom_arxiu_mat,'file')
    RAW = load(nom_arxiu_mat);
    Taula_15 = RAW.Taula_15;
    return;
end

% Info
fprintf('Important arxiu CSV...\n');

% Upload CSV file to Table: Energy-Date-Time
Taula_Minutal = Carrega_Taula_Minutal ( nom_fitxer_csv, 3, Inf, dateFormats );

% Info
fprintf('Generant Taula_15...\n');

% We generate table and fill the first row
nmax = find(~isnan(Taula_Minutal.Energia)); % Lines containing useful data
imax = nmax(end); % Number of lines to process
i = 1; k = 1; % Accountants
Taula_15 = table(); % Let's reset table_15
Taula_15.Data(1,1) = Taula_Minutal.Data(i+7); % Let's take the date in the middle of the interval (i + 7)
Taula_15.Hora(1,1) = Taula_Minutal.Hora(1); % Time
Taula_15.Hora(1,1).Second = 0; % Let's set seconds to zero
Taula_15.Energia(1,1) = sum(Taula_Minutal.Energia(i:i+14)); % Add block of 15 and save the variable
Taula_15.Potencia(1,1) = Taula_15.Energia(1,1) * 4; % Calculate Power
i = i + 15; k = k + 1; % We increase counters

% We fill the table net
while i < (imax-14) % As long as there are lines to process ...

    % Data
    % Let's take the date in the middle of the interval (i + 7)
    nous_valors{1} = Taula_Minutal.Data(i+7);

```

```
    % Time
    nous_valors{2} = Taula_15.Hora(1,1);
    nous_valors{2}.Minute = nous_valors{2}.Minute + (k-1)*15;

    % Energy (sum of block values of 15 minutes)
    nous_valors{3} = sum(Taula_Minutal.Energia(i:i+14));

    % Calculate Power
    nous_valors{4} = nous_valors{3} * 4;

    % We add new row to the table
    Taula_15 = [Taula_15;nous_valors]; %#ok

    % We increase counters
    i = i + 15;
    k = k + 1;

end

% Save file so that it does not reload
save(nom_arxiu_mat,'Taula_15');

% Info
fprintf('Fet.\n');

end

function Taula_Minutal = Carrega_Taula_Minutal ( ...
    filename, startRow, endRow, dateFormats )
% Load_Minutal_Table
%   Load a csv with minute data
%
% Generated by Matlab

%Initialize variables.
delimiter = {' ',';'};
if nargin<=2
    startRow = 3;
    endRow = inf;
end

% Read columns of data as text:
% For more information, see the TEXTSCAN documentation.
formatSpec = '%s%s%s%[^\n\r]';

% Open the text file.
fileID = fopen(filename,'r');

% Read columns of data according to the format.
% This call is based on the structure of the file used to generate this
% code. If an error occurs for a different file, try regenerating the code
% from the Import Tool.
disp('Importing...');
dataArray = textscan(fileID, formatSpec, endRow(1)-startRow(1)+1, 'Delimiter', delimiter, 'TextType', 'string', 'HeaderLines', startRow(1)-1, 'ReturnOnError', false, 'EndOfLine', '\r\n');
for block=2:length(startRow)
    frewind(fileID);
    dataArrayBlock = textscan(fileID, formatSpec, endRow(block)-startRow(block)+1, 'Delimiter', delimiter, 'TextType', 'string', 'HeaderLines', startRow(block)-1, 'ReturnOnError', false, 'EndOfLine', '\r\n');
    for col=1:length(dataArray)
        dataArray{col} = [dataArray{col};dataArrayBlock{col}];
    end
end

% Close the text file.
fclose(fileID);

% Convert the contents of columns containing numeric text to numbers.
% Replace non-numeric text with NaN.
disp('Replacing NaN...');
raw = repmat({''},length(dataArray{1}),length(dataArray)-1);
for col=1:length(dataArray)-1
    fprintf('  %d/%d\n',col,length(dataArray)-1);
    raw(1:length(dataArray{col}),col) = mat2cell(dataArray{col}, ones(length(dataArray{col}), 1));
end
numericData = NaN(size(dataArray{1},1),size(dataArray,2));

% Converts text in the input cell array to numbers. Replaced non-numeric
% text with NaN.
disp('Converting...');
rawData = dataArray{1};
for row=1:size(rawData, 1)
    if(mod(row,10^(log10(size(rawData, 1))-1))==0)
        fprintf('  %d/%d\n',row,size(rawData, 1));
    end
    % Create a regular expression to detect and remove non-numeric prefixes and
    % suffixes.
    regexstr = '(?<prefix>.*?)(?<numbers>([-]*(\d+[\,]*)+[\.]{0,1}\d*[eEdD]{0,1}[-+]*\d*[i]{0,1})|([-]*(\d+[\.]*)*[\,]{1,1}\d+[eEdD]{0,1}[-+]*\d*[i]{0,1}))(?<suffix>.*)';
    try
        result = regexp(rawData(row), regexstr, 'names');
        numbers = result.numbers;

        % Detected commas in non-thousand locations.
        invalidThousandsSeparator = false;
        if numbers.contains('.')
            thousandsRegExp = '^\d+?(\,\d{3})*\.{0,1}\d*$';
            if isempty(regexp(numbers, thousandsRegExp, 'once'))
                numbers = NaN;
```

```
                invalidThousandsSeparator = true;
            end
        end
        % Convert numeric text to numbers.
        if ~invalidThousandsSeparator
            numbers = textscan(char(strrep(numbers, ',', '.')), '%f');
            numericData(row, 1) = numbers{1};
            raw{row, 1} = numbers{1};
        end
    catch
        raw{row, 1} = rawData{row};
    end
end

dateFormatIndex = 1;
blankDates = cell(1,size(raw,2));
anyBlankDates = false(size(raw,1),1);
invalidDates = cell(1,size(raw,2));
anyInvalidDates = false(size(raw,1),1);
for col=[2,3]% Convert the contents of columns with dates to MATLAB datetimes using the specified date format.
    try
        dates{col} = datetime(dataArray{col}, 'Format', dateFormats{col==[2,3]}, 'InputFormat', dateFormats{col==[2,3]}); %#ok<AGROW>
    catch
        try
            % Handle dates surrounded by quotes
            dataArray{col} = cellfun(@(x) x(2:end-1), dataArray{col}, 'UniformOutput', false);
            dates{col} = datetime(dataArray{col}, 'Format', dateFormats{col==[2,3]}, 'InputFormat', dateFormats{col==[2,3]}); %#ok<AGROW>
        catch
            dates{col} = repmat(datetime([NaN NaN NaN]), size(dataArray{col})); %#ok<AGROW>
        end
    end

    dateFormatIndex = dateFormatIndex + 1;
    blankDates{col} = dataArray{col} == '';
    anyBlankDates = blankDates{col} | anyBlankDates;
    invalidDates{col} = isnan(dates{col}.Hour) - blankDates{col};
    anyInvalidDates = invalidDates{col} | anyInvalidDates;
end
dates = dates(:,[2,3]);

% Split data into numeric and string columns.
rawNumericColumns = raw(:, 1);

% Replace non-numeric cells with NaN
R = cellfun(@(x) ~isnumeric(x) && ~islogical(x),rawNumericColumns); % Find non-numeric cells
rawNumericColumns(R) = {NaN}; % Replace non-numeric cells

% Create output variable
Taula_Minutal = table;
Taula_Minutal.Energia = cell2mat(rawNumericColumns(:, 1));
Taula_Minutal.Data = dates{:, 1};
Taula_Minutal.Hora = dates{:, 2};

disp('Done.');

end
```

N Generate table 15 BATT

```
function [ Taula_15_BATT ] = Calcula_Taula_15_BATT ( Taula_15, BATT, ...
    tipus_llei_control, verbose )
%Calcula_Taula_15_BATT
%   Generates a Table_15 with the values of energy and power with BATT
%


% We assign date / time variables to Table_15_BATT
Taula_15_BATT = table(Taula_15.Data,'VariableNames',{'Data'});
Taula_15_BATT.Data_Local = Taula_15.Data_Local;

% We precalculate table length
lt = length(Taula_15.Potencia);

% We initialize variables
energia_consumida_amb_batt = zeros(lt,1);
fluxos_energia_batt = zeros(lt,1);
estat_bateries = cell(lt,1);
carrega_bateries = zeros(lt,1);

% For each 15min block of the table ...
for i=1:lt

    % Info
    if(mod(i,360)==0) && verbose % Show info every 360 blocks
        fprintf(' Bloc %d/%d (%.0f%%)\n',i,lt,i/lt*100);
    end

    % We save data from the table corresponding to the current block
    data_i = Taula_15.Data_Local(i); % Date in Local Time
    hora_i = data_i.Hour; % Current time
    minut_i = data_i.Hour; % Current time
    potencia_contractada_i = Taula_15.Potencia_contractada(i); % contracted power [kW]
    potencia_consumida_i = Taula_15.Potencia(i); % Power consumed [kW]
    potencia_disponible_i = potencia_contractada_i - potencia_consumida_i;
```

```
    energia_consumida_i = Taula_15.Energia(i); % Energy consumed [kWh]
    Px = Taula_15.Periode(i); % Current period

    % We select variables for the current day
    if i==1 || (hora_i==0 && minut_i==0) % At the beginning of a day ...

        % Indexes of the day
        i0 = i; % Index of the start of the day
        i1 = i0 + 24*4; % End of day index
        if i==1, i1 = i0 + 24*4 - 4; end % The first day starts at 1:00
        if i1>lt, i1 = lt; end % Last day of Table_15
        idx_dia = i0:i1; % Array of indexes of the day

        % Periods of the day
        periodes_dia = Taula_15.Periode(idx_dia); % All periods
        periodes_dia_unique = unique(periodes_dia); % Unique periods

        % Excess power of the day
        registre_exces_potencia_dia = Taula_15.Registre_exces_potencia(idx_dia);

        % For each period of the day, order the possible peaks
        idx_Px_ordenats = []; % Variable reset
        for p=1:length(periodes_dia_unique) % For each period of the day ...
            Pxu = periodes_dia_unique(p); % Period x (unique)
            idx_Px = ismember(periodes_dia,Pxu); % Indices (local) for Px
            peaks_Px = registre_exces_potencia_dia(idx_Px); % Excess power for Px
            idx_dia_Px = idx_dia(idx_Px); % Indices of the day for Px
            [peaks_Pxo,idxo] = sort(peaks_Px); % Order Excess Power for Px
            idxo = idxo(peaks_Pxo>0); % Select only excesses
            idx_Px_ordenats = [idx_Px_ordenats,idx_dia_Px(idxo)]; %#ok Px indexes ordered
        end

        % We look for power peaks (if any)
        idx_Px_ordenats_batt = [];
        if ~isempty(idx_Px_ordenats)

            % We add energy consumed in the power peaks
            energia_peaks = Taula_15.Energia(idx_Px_ordenats);
            potencia_contractada_peaks = Taula_15.Potencia_contractada(idx_Px_ordenats);
            energia_peaks_incremental = cumsum(energia_peaks - potencia_contractada_peaks/4);

            % We look for index for maximum battery capacity
            idx_batt = find(energia_peaks_incremental>BATT.carrega_maxima);
            if isempty(idx_batt), idx_batt = length(energia_peaks_incremental) + 1; end

            % We select set of peaks that the battery can absorb
            idx_Px_ordenats_batt = idx_Px_ordenats(1:(idx_batt(1) - 1));

        end

    end

    % We apply BATT
    switch tipus_llei_control
        case 'Compraventa'
            [ BATT, estat, flux_energia_batt ] = ...
                Llei_Control_Compraventa ( BATT, ...
                periodes_dia_unique, Px, ...
                potencia_disponible_i );
        case 'PeakShaving'
            [ BATT, estat, flux_energia_batt ] = ...
                Llei_Control_PeakShaving ( BATT, ...
                periodes_dia_unique, Px, ...
                potencia_disponible_i, ...
                idx_Px_ordenats_batt, i, verbose );
    end

    % We calculate Energy consumed, with active batteries
    energia_consumida_amb_batt_i = energia_consumida_i + flux_energia_batt;

    % Save variables of interest
    estat_bateries{i} = estat; % Battery status over time
    carrega_bateries(i) = BATT.estat_de_carrega_actual;
    fluxos_energia_batt(i) = flux_energia_batt;
    energia_consumida_amb_batt(i) = energia_consumida_amb_batt_i;

end

% We save variables in Table_15_BATT
Taula_15_BATT.Energia = energia_consumida_amb_batt;
Taula_15_BATT.Potencia = Taula_15_BATT.Energia * 4;
Taula_15_BATT.Flux_Energia = fluxos_energia_batt;
Taula_15_BATT.Estat_bateries = estat_bateries;
Taula_15_BATT.Carrega_bateries = carrega_bateries;

end
```

O Batteries plot

```
function [  ] = Plot_Bateries ( mes, Taula_15_BATT, ...
    Taula_Facturacio_6X_BATT, opts, extra )
%Plot_Bateries
%   Graph the magnitudes of the batteries in a Facturacio_BATT calculation
%
```

```
% Inputs:
%    month: specific month to graph. For annual graphs: month = 0
%    Table_15_BATT: Table with data in quarterly format
%    Taula_Facturacio_6X_BATT: Table with billing by periods
%    opts: plotting options
%    extra: extra string to be used as a suffix in filenames
%
% Outputs:
%   n/a
%


% We select the study period
if mes == 0 % Annual
    mes_i = 1:12;
    mes_str = 'Anual';
    idx = true(length(Taula_15_BATT.Data),1); % Tot l'any
else % Month selected
    mes_i = mes;
    mes_str = Taula_Facturacio_6X_BATT.Properties.VariableNames{mes_i};
    idx = Taula_15_BATT.Data_Local.Month == mes_i;
end

% Replaces names of the month
if strcmpi(mes_str,'Mars'), mes_str = 'Mars'; end

% File name suffix
sufix = sprintf('%02.0f_%s',mes,mes_str);

% We add extra suffix, if applicable
if nargin>4 && ~isempty(extra)
    sufix = [sufix,'.',extra];
end

% We extract study variables (BATT)
data_mes = Taula_15_BATT.Data_Local(idx); % Dates of the study period
fluxos_energia_batt_mes = Taula_15_BATT.Flux_Energia(idx);
estat_bateries_mes = Taula_15_BATT.Estat_bateries(idx);
carrega_bateries_mes = Taula_15_BATT.Carrega_bateries(idx);

% Energy Flow
fh = figure();
hold on, box on; grid on;
plot(data_mes,fluxos_energia_batt_mes);
title(['Flux d''Energia cap a la BATT per bloc quarthorari | ',mes_str]);
ylabel('Energia [kWh]');
xlim([data_mes(1),data_mes(end)]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.BATT_Flux_Energia.',sufix,'.png']));
close(fh);

% BATT load
fh = figure();
hold on, box on; grid on;
plot(data_mes,carrega_bateries_mes);
title(['Carrega de la BATT per bloc quarthorari | ',mes_str]);
ylabel('Energia [kWh]');
xlim([data_mes(1),data_mes(end)]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.BATT_Carrega.',sufix,'.png']));
close(fh);

% State of the BATT
fh = figure();
hold on, box on; grid on;
estats_batt = {'repos','carregant','descarregant'};
for i=1:length(estats_batt)
    estat_batt = estats_batt{i};
    idx2 = ismember(estat_bateries_mes,estat_batt);
    aux = i*ones(length(idx2),1);
    aux(~idx2) = NaN;
    plot(data_mes,aux,'-','LineWidth',2');
end
legend(estats_batt{:},'Location','NorthEast');
title(['Estat de la BATT per bloc quarthorari | ',mes_str]);
xlim([data_mes(1),data_mes(end)]);
ylim([0,length(estats_batt)+2]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.BATT_Estat.',sufix,'.png']));
close(fh);

end
```

P Consumption plot

```
function [  ] = Plot_Consums ( mes, Taula_15, Taula_Facturacio_6X, ...
    opts, extra )
%Plot_Consums
%   Graph consumption of a billing calculation
%
% Inputs:
%    month: specific month to graph. For annual graphs: month = 0
%    Table_15: Table with data in quarterly format
%    Taula_Facturacio_6X: Table with billing by periods
```

```matlab
%    opts: plotting options
%    extra: extra string to be used as a suffix in filenames
%
% Outputs:
%   n/a
%


% We select the study period
if mes == 0 % Annual
    mes_i = 1:12;
    mes_str = 'Anual';
    idx = true(length(Taula_15.Data),1); % The whole year
else % Month selected
    mes_i = mes;
    mes_str = Taula_Facturacio_6X.Properties.VariableNames{mes_i};
    idx = Taula_15.Data_Local.Month == mes_i;
end

% Replaces names of the month
if strcmpi(mes_str,'Mars'), mes_str = 'Mars'; end

% File name suffix
sufix = sprintf('%02.0f_%s',mes,mes_str);

% We add extra suffix, if applicable
if nargin>4 && ~isempty(extra)
    sufix = [sufix,'.',extra];
end

% We extract study variables
data_mes = Taula_15.Data_Local(idx); % Dates of the study period
potencia_contractada_mes = Taula_15.Potencia_contractada(idx); % Pot contract [kW]
potencia_consumida_mes = Taula_15.Potencia(idx); % Power consumed [kW]
energia_consumida_mes = Taula_15.Energia(idx); % Energy consumed [kWh]
exces_potencia_mes = Taula_15.Registre_exces_potencia(idx); % Excess Power [kW]

% Power Consumption + Contracted Power
fh = figure();
hold on, box on; grid on;
plot(data_mes,potencia_contractada_mes);
plot(data_mes,potencia_consumida_mes);
plot(data_mes(exces_potencia_mes>0),...
    potencia_consumida_mes(exces_potencia_mes>0),'.');
legend('Contractada','Consumida','Exces de Potencia',...
    'Location','SouthWest');
title(['Consum de Potencia per bloc quarthorari | ',mes_str]);
ylabel('Potencia [kW]');
xlim([data_mes(1),data_mes(end)]);
ylim([0,8000]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Consum_Potencia.',sufix,'.png']));
close(fh);

% Energy consumption
fh = figure();
hold on, box on; grid on;
plot(data_mes,energia_consumida_mes);
title(['Consum Energia per bloc quarthorari | ',mes_str]);
ylabel('Energia [kWh]');
xlim([data_mes(1),data_mes(end)]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Consum_Energia.',sufix,'.png']));
close(fh);

% Energy consumption by periods
fh = figure();
hold on, box on; grid on;
y = zeros(6,1);
for p=1:6
    y(p) = sum(Taula_Facturacio_6X{7+p,mes_i}) * 1E-3; % Value of the period Pi
    bar(p,y(p)); % Bar chart
    text(p,y(p)+1,sprintf('%.2f',y(p)),... % We show value on the bar
        'HorizontalAlignment','center',...
        'VerticalAlignment','bottom');
end
title(['Consum Energia per Periode | ',mes_str]);
ylabel('Energia [kWh]');
xlabel('Periode');
ylim([0,max(y)*1.2]); % Maximum total for the whole year
xlim([0,7]); % We leave room for it to be centered
xticks(1:6); % Show only periods, not margins (0.7)
xticklabels({'P1','P2','P3','P4','P5','P6'}); % We show text in values
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Consum_Energia_Px.',sufix,'.png']));
close(fh);

% Excess Power Record
fh = figure();
hold on, box on; grid on;
plot(data_mes,exces_potencia_mes);
title(['Registre Exces Potencia per bloc quarthorari | ',mes_str]);
ylabel('Potencia [kW]');
xlim([data_mes(1),data_mes(end)]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Registre_Exces.',sufix,'.png']));
close(fh);

end
```

Q Billing plot

```
function [  ] = Plot_Facturacio ( mes, Taula_15, Taula_Facturacio_6X, ...
    opts, extra )
%Plot_Facturacio
%   Graphic billing of a Billing calculation
%
% Inputs:
%     month: specific month to graph. For annual graphs: month = 0
%     Table_15: Table with data in quarterly format
%     Taula_Facturacio_6X: Table with billing by periods
%     opts: plotting options
%     extra: extra string to be used as a suffix in filenames
%
% Outputs:
%   n/a
%


% We select the study period
if mes == 0 % Annual
    mes_i = 1:12;
    mes_str = 'Anual';
    idx = true(length(Taula_15.Data),1); % Tot l'any
else % Month selected
    mes_i = mes;
    mes_str = Taula_Facturacio_6X.Properties.VariableNames{mes_i};
    idx = Taula_15.Data_Local.Month == mes_i;
end

% Replaces names of the month
if strcmpi(mes_str,'Mars'), mes_str = 'Mars'; end

% File name suffix
sufix = sprintf('%02.0f_%s',mes,mes_str);

% We add extra suffix, if applicable
if nargin>4 && ~isempty(extra)
    sufix = [sufix,'.',extra];
end

% We extract study variables
data_mes = Taula_15.Data_Local(idx); % Dates of the study period
facturacio_energia_mes = Taula_15.Facturacio_energia(idx); % Energy billing [\euro]

% Energy Billing
fh = figure();
hold on, box on; grid on;
plot(data_mes,facturacio_energia_mes);
title(['Facturacio Energia per bloc quarthorari | ',mes_str]);
ylabel('Cost [\euro]');
xlim([data_mes(1),data_mes(end)]);
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Facturacio_Energia.',sufix,'.png']));
close(fh);

% Energy billing by periods
fh = figure();
hold on, box on; grid on;
y = zeros(6,1);
for p=1:6
    y(p) = sum(Taula_Facturacio_6X{p,mes_i}) * 1E-3; % Value of the period Pi
    bar(p,y(p)); % Bar chart
    text(p,y(p)+1,sprintf('%.2f',y(p)),... % We show value on the bar
        'HorizontalAlignment','center',...
        'VerticalAlignment','bottom');
end
title(['Facturacio Energia per Periode | ',mes_str]);
ylabel('Cost [milers \euro]');
xlabel('Periode');
ylim([0,max(y)*1.2]); % Maximum total for the whole year
xlim([0,7]); % We leave room for it to be centered
xticks(1:6); % Show only periods, not margins (0.7)
xticklabels({'P1','P2','P3','P4','P5','P6'}); % We show text in values
print(fh,'-dpng','-r300',fullfile(opts.odir,...
    [opts.nom_simulacio,'.Facturacio_Energia_Px.',sufix,'.png']));
close(fh);


end
```