Modelling Li-ion battery aging for second life business models

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El Perquè De Tot Plegat

- Jo de gran vull ser descobridor – vaig dir a la professora – com ma mare!

Era la manera que tenia jo de concebre la recerca. Als meus ulls, la mare era la Indiana Jones (o Indiana Jonessa) de la ciència. Me la imaginava amb el barret i el fuet caminant pels passadissos de la universitat, amb terra lluent de marbre, buscant aquella escletxa, aquella petita marca a la paret que obria portes invisibles a mirades inexpertes.

Alguns dissabtes ens trobàvem esperant que acabés algun article que, de tan important, crec que li anava la vida. No parava de dir que s'apropava el "Deadline", que jo imaginava com una mena de serp gegant que sortia dels lavabos bruts de portes guixades amb crits d'independència i insults feixistes que aleshores encara no entenia. Quan enllestia sortia corrent, fugint d'un tal "Call", tot al·legant que ja l'encararia el dilluns, que aquella revista tenia un JCR molt alt i això era imprescindible. Aleshores anàvem a la "Les Vilas", la platja o on fos. Quan als vespres, sota una llum tènue de vella bombeta, la mare es tornava a capbussar en el paperam, el pare ens explicava contes emocionantíssims i delirants on ma germana i jo erem els protagonistes. En acabat, trobàvem la mare adormida amb els papers a les mans, plens d'enigmes i jeroglífics que deien haver trobat una novetat que revolucionaria el món, una nova manera d'enfocar quelcom que jo no podia entendre.

A més, la mare també tenia un tutor mentre feia allò que anomenava "la Tesi", que intuïa una mena de puzzle gegant perquè no parava de dir que no sabia com resoldre aquell trencaclosques. I això em tranquil·litzava, perquè a l'escola jo també tenia tutors que m'ajudaven quan no sabia resoldre problemes.

Potser va ser aquesta màgia, aquesta incògnita permanent, aquesta inquietud per descobrir barrejat amb la imaginació paterna. Potser per això també m'agrada la idea d'escriure i acabar fent recerca.

Vaig néixer just quan la mare començava la Tesi i el pare ja treballava en una multinacional química on ha estat treballant fins que s'ha jubilat.

Ara sóc jo qui es baralla amb "La Tesi", qui passa els estius pensant com resoldre certs maldecaps, qui puja i baixa per la muntanya russa emocional que significa fer el doctorat, qui corre per arribar a temps als "deadlines" i "due dates", qui busca algun "call" de revista JCR que sigui interessant, qui viatja per anar a congressos, qui té no només un sinó 2 tutors que l'ajuden i exigeixen i qui, al capdavall, ha acabat tenint la Bruna en el procés.

Alguna cosa dec haver anat aprenent amb el pas del temps...

Gràcies.

Acknowledgements

Aquesta tesis no hagués estat possible, en primera instància, sense els malabarismes de la Dra. Margarita González. Per poc no em costa un cobriment de cor i una temporada a l'atur, però les peripècies han donat els seus fruits.

Vull agrair, enormement, l'esforç i dedicació de la Dra. Beatriz Amante, la gran directora de Tesi. Partint de no res hem aconseguit molt (m'atreviria a dir). El teu afany i la constant pressió per publicar han fet que, al capdavall, l'escriptura final de la tesi hagi estat més senzilla del que pensava (i que consti que no ha estat fàcil!). A més de servir per tenir una bona colla d'articles, quatre dels quals relativament potents, també hem aconseguit un premi que, vulguis que no, sempre puja la moral. Junts ens hem ficat en un bon grapat d'entramats empresarials i de centres de recerca en aquesta folla persecució de finançament. A hores d'ara, encara cal veure com acaba tot aquest enrenou, però ha estat interessant i sorprenent.

Gràcies a totes dues i al Dr. Santiago Gassó, director del departament, per ajudar-me a continuar dins aquest interessant col·lectiu que és la UPC.

No puc oblidar-me dels companys de despatx. Fan que les tardes, quan el Sol pica directe als vidres i es reflexa a la pantalla, siguin menys sufocants i que els dinars dels migdies s'omplin de rialles a l'intentar comprendre l'actualitat política del país. Victor, a veure quan entres a la taula de l'aigua de Terrassa i et poses a netejar-la de veritat!! Maria, visca els models castastrofistes! Quan desapareixi l'aeroport del Prat sota el mar diré que ja sabia que passaria. Marcel, a veure si portes, algun dia que ningú miri, aquelles cerveses artesanals que saps fer.

També al Carlos, que sense fer soroll et soluciona tot allò que necessites. I al Robert, que tot just acaba d'arribar i em recorda els meus principis, quan intentava entendre com era això d'una bateria de liti.

No s'escapen dels agraïments tots els companys de la SEAT. Al Santi Castellà, el meu referent i co-tutor a la SEAT, per ser tant perfeccionista amb les presentacions i l'estètica, tot plegat s'acaba notant. Juntament amb el Jordi Caus (si mai canvies de feina, avisa'm, així potser sabré, d'avançada, on acabaré aterrant), per ficar-me en un batibull de projectes que no acabaven d'arrencar però que al final estan tots en marxa. A part de la molta feina i maldecaps que han suposat, haig d'acceptar que, al capdavall, també han acabat servint per més del que em pensava, gràcies a ells hi ha alguna que altra presentació en congressos i, sobretot, un munt de contactes. També vull agraïr a l'Antonio Merino, de qui m'enduc uns mòduls per practicar a la universitat i al Gerhard Lux i la seva marca de cosmètics. No m'oblido de tota la colla del (i que ha passat pel) laboratori de bateries: Francesc Sabaté (esto hase culebra), Marc (Per la gateway i paciència infinita), Xavi(El català correcte, passa'l!), Victor (No estava adormit, va ser una goma de plàstic que em va deixar l'ull mig tancat), Patri (LA, en singular dins aquest món masculí), David (El bentornat que va ocupar tot un "encuentro informativo"), Jose (vist i no vist) i Sebastian (Cañita), que aconseguiu que l'invisible pugui ser mostrat amb orgull.

Al Zumba, Simbad, Who's bad, SunBath o com se digui.

En un grup entre Universitat i SEAT, hi ha els *Doctorandos Anónimos*, que d'anònims res però que si que han servit perquè els plors d'uns serveixin per suavitzar els drames dels altres.

Un bon grup de teràpia: Adrián, amb la seva mà d'informàtic manipulador i amb qui he publicat un bon article; Armand, em quedaré sempre amb la frase: Jo no dic mai res que no sigui cert; Carlos, el finançador; Daniel, qui tot s'ho gasta; Javi, que poc a poc i sense fer soroll va fent; Jorge, ànims amb els *reviewers*, que ja veuràs que no n'hi ha per tant; Miguel i Xavier, el primer, l'alliberat, el guia.

També cal agraïr explícitament als finançadors de la beca que han permès que pugui dedicar tres anys per escriure aquestes poques pàgines: la Universitat Politècnica de Catalunya i el Centre Tècnic de SEAT.

Als amics de sempre. Per riure's de les meves penes, simulacions i condició de becari als 35. Per seguir estant allà i per animar-vos a ballar! La vida continua més enllà de la Tesi! Especialment a aquells que ja heu passat per aquest tràngol, al principi no em creia aquella frase de: Ho vaig veure més clar quan vaig fer el projecte de Tesi. Teníeu raó.

A la família, completa, per interessar-se pel que faig encara que sigui per sobre. Per les trobades, les sortides i l'enrenou i per facilitar-nos l'habitatge i les transaccions a la UPC ;)

Als pares (i avis), que ja tenen una pàgina pròpia. I a la Júlia, per perseguir allò que es vol i ensenyar-me que és possible fer allò que vols fer a la vida (encara que no sigui un camí de roses). Girona queda una mica lluny amb tanta novetat, però intento que els esdeveniments recents et siguin propers!

Finalment, a qui m'acompanya des de fa més de 15 anys, la que *me encontré (i me encontró) en la calle.* Laia, faré un resum per no allargar-me massa i no quedar massa cursi. Gràcies per entendre que estigués *out* en alguns (molts) moments, per animar-me quan estava a les valls de la muntanya russa emocional que han estat aquests tres anys, per organitzar mil caps de setmana i planificar escapades a mesos vista. Gràcies pels consells estètics i per la paciència, sé que tens quasi tantes ganes com jo de que l'acabi! I gràcies per animar-te a compartir la "cosa". Va costar, tot plegat, però al final no va caldre ni tan sols fer servir el mètode fenomenalogic per trobar-li nom.

I clar, a la Bruna. Per riure als matins després de molestar tota la nit, com vols que ens enfadem si ens despertes així? Per bellugar els bracets i les cames sense gaire ordre. Per fer xiscles d'emoció i monòlegs increïbles. Per indicar-nos que tens gana o vols dormir. Per ser tant soferta. Per destarotar l'ordre de les coses, els avis i el col·lectiu familiar.

Gràcies per venir.

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Glossary

ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
BMC	Battery Management Control
BMS	Battery Management System
B2G	Battery to Grid
CAES	Compressed Air Energy Storage
CAT	Authorized Treatment Centers
CTS	Centro Técnico SEAT
DOD	Depth Of Discharge
EIS	Electrochemical Impedance Spectroscopy
EMS	Energy Management System
EoL	End of Life
EPRI	Electric Power Research Institute
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FU	Functional unit
GHG	Greenhouse Gass
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test Cycle
ICEV	Internal Combustion Engine Vehicle
IREC	Institut de Recerca en Energia de Catalunya
LCA	Life Cycle Assessment
LCCO2	Life Cycle Carbon Dioxide Assessment
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate
LVP	Lithium vanadium phosphate
NEDC	New European Driving Cycle
NMC	Lithium Nickel Manganese Cobalt Oxide
NCA	Lithium Nickel Cobalt Aluminium Oxide
NiMH	Nickel–Metal Hydride
NYCC	New York City Cycle
OBC	On-Board Charger
OCV	Open Circuit Voltage
PHEV	Plug-In Hybrid Electric Vehicle
RC	Resistance and Capacitator
RES	Renewable Energy Sources
RUL	Rest of Useful Life

SEI	Solid Electrolyte Interface
SOC	State Of Charge
SOH	State Of Health
TTW	Tank-to-Wheel
UPS	Uninterruptible Power Supply
UDDS	Urban Dynamometer Driving Schedule
UPC	Universitat Politècnica de Catalunya
US06	Supplemental Federal Test Procedure
V2G	Vehicle To Grid
WLTC	Worldwide harmonized Light duty driving Test Cycle
WTW	Well-to-Wheel
WTT	Well-to-Tank

Chapter 1

Organization

Conviene aclararlo de una vez por todas:
La revolución no es jamás suicidio
La revolución ni siquiera es la muerte
La revolución es la vida más que ninguna otra cosa

Mario Benedetti, "*El cumpleaños de Juan Ángel*".

1.1 Motivation

The Electric Vehicle (EV) business is not being as successful as expected, mostly because of battery prices and lifespan, which slowed down the selling. Trying to turn this tendency into profit, car manufacturers are searching possible alternatives to obtain some revenues back. The 2^{nd} life of EV batteries is being seriously analyzed by most of them as a possible solution. It was then, something more than three years ago, that SEAT thought it was a good opportunity to study the business opportunities of this battery reuse idea and decided to do this research by means of a PhD student.

Battery aging on 2^{nd} life applications was defined as the focus of this thesis during the State of the Art analysis, when we saw that there was a lack of knowledge and research in this field and that it was a good departing point for this thesis.

1.2 Organization

This thesis should be understood as the result of the interest of SEAT and the Universitat Politècnica de Catalunya (UPC) in businesses and research beyond electro-mobility, and, at the same time that the university gets closer to industry needs and reality while the industry gains scientific knowledge getting deeper into the research from R&D&i. In fact, some of the information exposed in the following chapters comes from the Sunbatt project developed in the Centro Técnico SEAT (CTS) installations.

As shown in Fig.1.1, the introduction starts in **Chapter 2**, which is intended to bring the reader into the reality of the EV. It presents some of the problems that EVs are facing and the expected solutions that car manufacturers are dealing with to overcome them. Moreover, **Chapter 2** describes the focus of this thesis: the study of the second life of EV batteries.

Chapter 3 presents an State of the Art of the energy storage business models, electrical models of Lithium ion batteries and the methods applied to introduce the battery aging phenomena into these models to simulate and determine the Rest of Useful Life (RUL) of these batteries on different second life scenarios.

Next, **Chapter 4** deals with the first issue to be analyzed in order to continue with the study of the second life of EV batteries. It is an overview of the EVs that are nowadays running around Europe and the differences concerning their batteries. This will help to go deep into the study of the re-purposing necessities and the different factors that should be taken into account. This chapter is based on the poster presented at the first Energy Systems Conference: When theory meets reality, entitled: *A review of the complexities of applying second life electric car batteries on energy businesses* that took place in London on June 23-25, 2014.

The following chapters delve into some of the re-purposing complexities, such as the strategies to manage the large number of battery models and packages, the costs, the State Of Health (SOH) assessment, the communications with the elements in the electricity grid and the technical transformations needed to use them on stationary applications.

Chapter 5 analyzes the communications between the EV battery and the electricity grid elements. From all the parameters used in the EV configuration, a small number of parameters are identified for battery control and management in stationary applications. Moreover, an analysis of the communications protocols and norms that vehicles and stationary devices commonly use are identified and a proposal of standardization is presented. This chapter also presents the necessary adaptations needed to use EV batteries in stationary environments. It is based on the article: *Communications concerns for reused electric vehicle batteries in smart grids* that is under the second revision round by the IEEE Communications Magazine.

Chapter 6 presents a first economical approach. It analyzes the costs of the re-purposing process alternatives EV batteries are subjected to when they finish their 1^{st} life. Apart from comparing the two main strategies for battery repurpose: direct reuse or module reuse, this

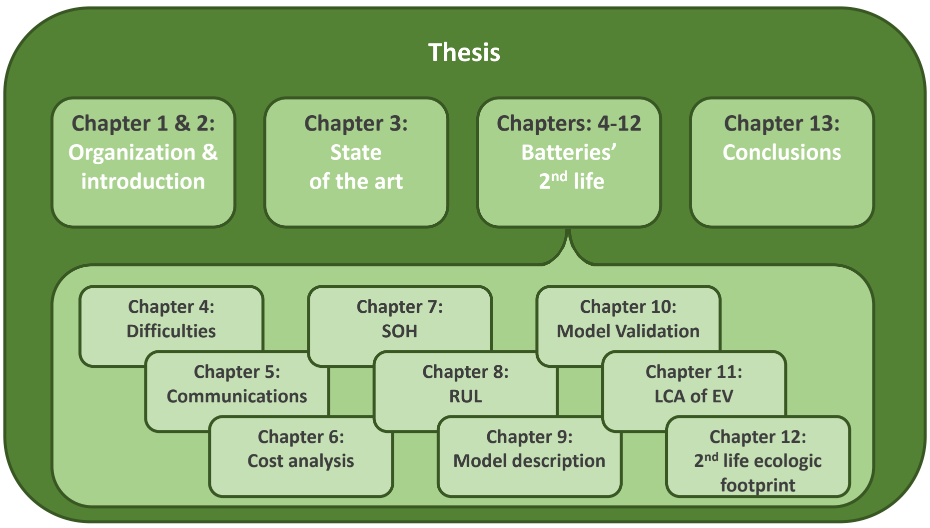


Figure 1.1: Thesis organization diagram

chapter takes into account the car dismantling, battery collection and transportation to the re-manufacture plant, electric tests, verification and, finally, shipment of the 2^{nd} life' batteries to their final destination. This chapter is based on an article entitled: *A cost analysis of electric vehicle batteries second life businesses* that was presented in the 18^{th} CIDIP congress that took place in Alcañiz on July 16-18, 2014. This paper was selected to be part of the Lecture Notes in Management and Industrial Engineering that ended in the published book by Springer: *Project Management and Engineering Research, 2014*, pages 129-141, DOI 10.1007/978-3-319-26459-2.

Chapter 7 deals with the SOH of batteries. The SOH defines the useful capacity of a battery, i.e, the quantity of energy it is able to offer. This parameter is a key factor to classify the batteries that best suit for each 2^{nd} life application. In this chapter, a new methodology to estimate the SOH using EV on board data is presented. This is useful to accelerate battery testing that, nowadays, is a highly time consuming process and represents an important part of the repurposing costs. This chapter is based on the article entitled: *PHEV battery ageing study using voltage recovery and internal resistance from On-board data* published in the IEEE Transactions on Vehicular Technology.

Once the SOH of a battery is identified, it is time to calculate the RUL for different end-users or final customers of 2^{nd} life applications. This is a basic information to calculate the minimum amortization costs for battery replacement and maintenance in stationary applications. An electric battery model is presented in **Chapter 8** based on literature experimental data and simulations are executed under different representative temperature and cycling modes. The results were presented in the 19^{th} CIDIP congress that took place in Granada on July 15-17, 2015. The article was entitled: *Ageing model for re-used electric vehicle batteries in second life stationary applications.* In this case, this paper was awarded with the *Accesit al Premio del Consejo General de Colegios Oficiales de Ingenieros Industriales* and, again, it was selected to be part of the Lecture Notes in Management and Industrial Engineering by Springer, although the book is not yet published.

To clearly identify the aforementioned model, an extensive description of the model developed in Mathlab using the Simulink tools is described in **Chapter 9**. It presents the assumptions taken and the working limitations the model has. Moreover, to fully comprehend its working applicability, some additional simulation's results are shown based on the presentations *Energy businesses from re-used electric vehicle batteries* and *Sunbatt: Use of a Second Life Battery System from PHEV in Stationary Applications* given in the Global Cleaner Production and Sustainable Consumption Conference and the Smart City Expo World Congress respectively that took place on November 2015.

Then, **Chapter 10** contains the "confidential" part of the Thesis. In this chapter the proposed aging electric model is validated comparing the simulation results with the aging values obtained from experimental tests of various battery cells submitted to accelerated aging profiles in laboratory test benches.

However, the reuse of EV batteries may offer other benefits, rather than just economic revenues, such as the reduction of CO_2 emissions, the introduction of decentralized electricity generation, the possibility to reduce energy losses in the grid by energy demand adjustment, etc. Therefore, an environmental approach is the focus of **Chapters 11** and **12**. The first chapter delves into the environmental impact of EVs and compares the environmental enhancement strategies of the energy and transportation sectors in different European countries. Chapter 11 is based on the paper under review in the Journal of Cleaner Production entitled: *Do e-mobility and energy policies match in Europe? Analysis of environmental benefits from electric vehicle use* that was written in cooperation with the IKERLAN research center from the Basque Country. On the other hand, **Chapter 12**, which is based on the article *Second life of electric vehicle batteries: relation between materials degradation and environmental impact* done in cooperation with the CIC-Energigune research center from the Basque country, studies the environmental impact of reused batteries depending on the 2^{nd} life application and how lifespan is a major concern for environmental impact reduction. Additionally, this paper analyzes different Li-ion technologies and materials used for the electrodes and defines how the research is mostly focused in power and energy density rather than in the environmental impact.

Finally, **Chapter 13** presents the conclusions of the whole thesis making a final and coherent closure. Additionally it will incorporate an overview of the possible future research lines in the aging of batteries and in the 2^{nd} life battery businesses.

Chapter 2

Introduction

Alice was beginning to get very tired of siting by her sister on the bank, and of having nothing to do: Once or twice she had peeped into the book her sister was reading, but it had no pictures or conversations in it, "and what is the use of a book," thought Alice, "without pictures or conversation?".

Lewis Carroll, "*Alice in wonderland*".

2.1 The electric vehicle

Although it seems that the EV is something new and the most promising alternative to Internal Combustion Engine Vehicle (ICEV) in the near future, the truth is that the first concept was presented in 1882 (fig.2.1 Left), four years before than the first ICEV was build. Both concepts were evolving in parallel during the firsts years and the electric-motion was even announced in local journals as a secure and cost effective transportation mode (fig.2.1 Right). Nevertheless, the ICEV finally imposed and its use was spread all over the world.

Nowadays, the consequences of the ICEV worldwide success is also its main drawback. The Greenhouse Gass (GHG) emissions from transportation suppose a 15% [1] of the total emissions estimated for Europe. The European Commission and its member states are introducing harder directives on the transportation sector in order to mitigate or reduce the total amount of CO_2 emissions.

Having no tailpipe emissions, the EV and Plug-In Hybrid Electric Vehicle (PHEV) (when driving electric) are presented as an interesting mobility alternative [2]. Consequently, the EV is, slowly but steadily, entering into the automotive market and increasing, year after year with the help of governmental incentives, its market share.

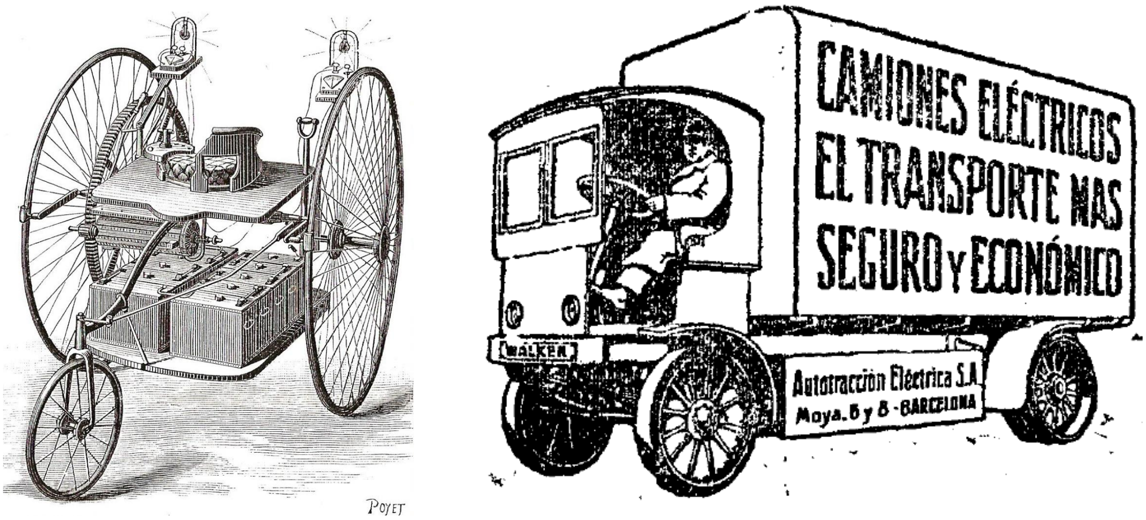


Figure 2.1: Left: Sketch of the first electric vehicle from Ayrton and Perry done in 1882. Right: Advertisement from the Barcelona's journal "La Vanguardia", 15th September 1925 .

The term EV refers to all vehicles propelled by electric motors. As there are many ways to store the electricity energy that will finally move the vehicle, such as fuel cells, capacitors, supercapacitors, compressed air, flywheels and batteries, there are many different types of EVs. However, this thesis is based on EVs using batteries, thus, from now on, the acronym EV will make reference to this kind of vehicles only.

Batteries store energy by chemical reactions. Then again, there are many different chemistry alternatives to build batteries, having each of them different properties and characteristics that will be used to select one or another battery technology. These characteristics are: Energy density, power density, temperature working range, lifespan or cycles and its price. Furthermore, the most used chemistry technologies to build batteries are: Lead acid, Nickel Cadmium (NiCd, although nowadays they are forbidden in most countries due to its environmental hazard), Nickel Metal Hydride (NiMH, used in many hybrid vehicle models), Flow batteries (Vanadium Redox, Polysulfide Bromide or Zinc Bromine), Sodium Sulfur (NaS), Sodium/Nickel Chloride (ZEBRA) and Lithium ion batteries (Li-ion). This thesis will deal with the last mentioned battery type, the Li-ion batteries, which are those finally being used worldwide in EVs by almost all car manufacturers. Fig.2.2 presents the evolution of the battery technology use for EV during the last decades [3].

Although Li-ion batteries have displaced almost all the other technologies their cost is still quite high making EV far from being competitive and affordable for the average population [4]. Car manufacturers choose different strategies to counteract this fact. Some companies lease the battery, so the initial EV price is more attractive and they can offer a good warranty to the client. Others search for alternatives, such as the re-use of the battery before recycling, which implies an additional cost for the car manufacturer.

When a battery ends its life in an EV (1st life hereinafter), it does not mean that it is useless. It only means that its performances are not as good as they were at the beginning. The capacity is reduced and the internal resistance increase implies an additional energy loss, lower efficiency and a loss of peak power [5], [6], [7]. Even though this performance reduction seems dramatic, it is not quite so. The car driver will hardly notice it because of the variability of everyday trips and driving conditions [8]. Nevertheless, car manufacturers prefer to give a good image rather than an ungrateful experience at the end of the EV life and have defined the battery end-of-life when its SOH reaches the 80-70% [9].

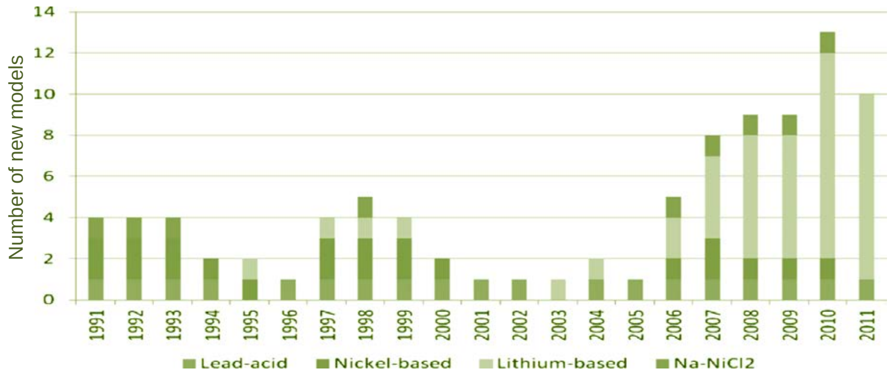


Figure 2.2: Evolution of the battery technology used on EVs during the last decades. Source: Sierzchula [3]

2.2 Where the road transportation and the electricity sector meet

Since last decade, the road transportation and the electricity sector were independent actors doing their business and products according to their particular interests and needs. With the entrance of the EV this paradigm has substantially changed and there are many points were these two sectors meet.

The first meeting point comes to fulfill a road transportation need, which is that the EV should be charged with electricity. Consequently, charging stations should be deployed around. However, a common EV charge takes around 5 to 8 hours to fully charge the battery. As the range anxiety is one of the major drawbacks of EV [10], fast charging stations are being developed and spread through the territory. Each of these fast charge station demand 50 kW peak power to the grid and lasts for about 20 minutes, which is quite high and problematic regarding the actual electricity infrastructures of cities and might cause grid unbalances and failures [11].

At the end of their 1st life, EV and PHEV batteries still have some energy capacity. In fact,

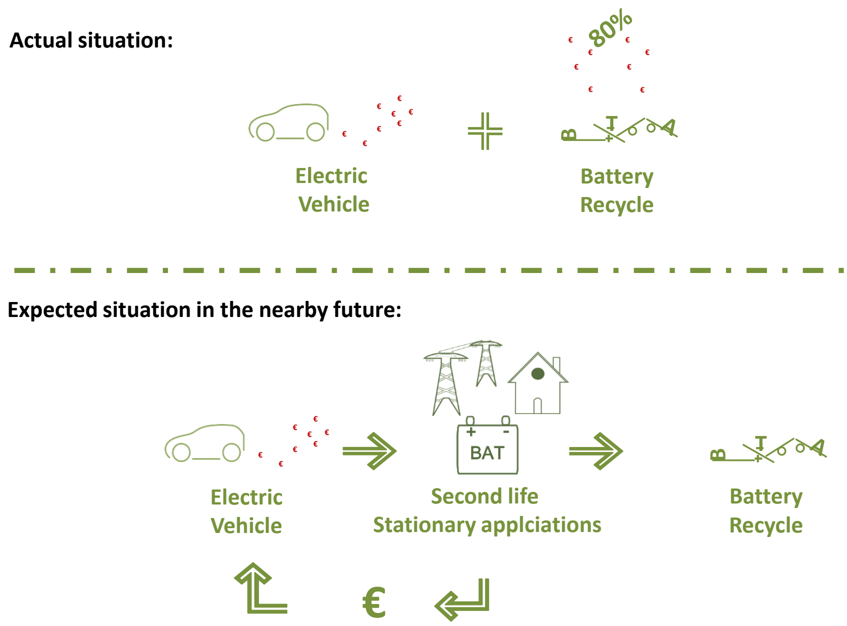


Figure 2.3: The electric vehicle battery can be used for other purposes before recycling.

the initial average 8 kWh from PHEV and 24 kWh from EV batteries' capacity [12] should finish their 1st life when their capacity is around 6.4 to 19.2 kWh (corresponding to the 80% as shown in Fig.2.3). This capacity is more than what actual lead acid batteries can afford. Considering that an average consumption of a house in Spain is around 10 kWh per day, these batteries could easily provide some home energy services. Nevertheless, if the batteries are grouped, as it is done with new batteries to form bigger energy storage systems, they could offer plenty of energy services.

In fact, energy storage systems are recently being claimed to solve many of the actual grid problems, such as the aforementioned grid overload and to provide additional energy services that could revert in economic profit.

This is the other meeting point of these two sectors but this time it is the road transportation who offers a solution to the electricity sector by providing less expensive batteries for stationary applications. Hence, what was considered a cost and recycling management issue is now perceived as an economic and a technical opportunity. This is represented by the schema in Fig.2.3 and it is the origin of this thesis: The search of 2nd life battery businesses to make the EV more attractive and competitive.

Some of the services that energy storage systems can provide are listed in table.2.1 with a small description of the expected added value.

All business studies start with a concept or idea, to further continue with an economic analysis. In order to calculate the profit, the amortization or the payback periods, it is needed to know the incomes generated by these businesses, the maintenance cost and, most important, the lifespan of the system. However, unlike working with new batteries, not all 2nd life batteries will have the same SOH. Moreover, if batteries evolve so they can provide more than 400 km mileage range for cars, it is provable that owners may decide to use it up for longer time and finish at even lower SOH. Therefore, the 80% SOH starting point is not ensured. Additionally, the aging or degradation of batteries will depend on the requirements of 2nd life applications.

Table 2.1: Services that energy storage systems can provide to the electricity system. Source: Akhil [[13]

Stationary Applications	Description
Black Start	Ability to achieve the operating conditions of a system after a shutdown without help of the grid.
Power oscillation damping	Ability to reduce the oscillation from lower frequencies.
Grid inertial response	Ability to maintain the frequency in the grid to sudden changes in the load.
Power gradient reduction	Capacity to reduce the sudden changes of variable power sources such as wind generators.
Energy Arbitrage	Buying and selling energy at different instants to maximize profit.
Peak Shaving	Shift of energy demand from higher to lower prices reducing the peak power demands
Load Following / Area regulation	Meet hour to hour and daily variations
Filtering / Firming renewable	Renewable energy sources do not ensure constant power supply; batteries can mitigate this drawback.
Primary and secondary reserve	Automatic regulation service in charge with restoring the balance between production and consumption.
Island operation mode	Batteries are useful to provide energy in island installations when the primary energy source is not available.

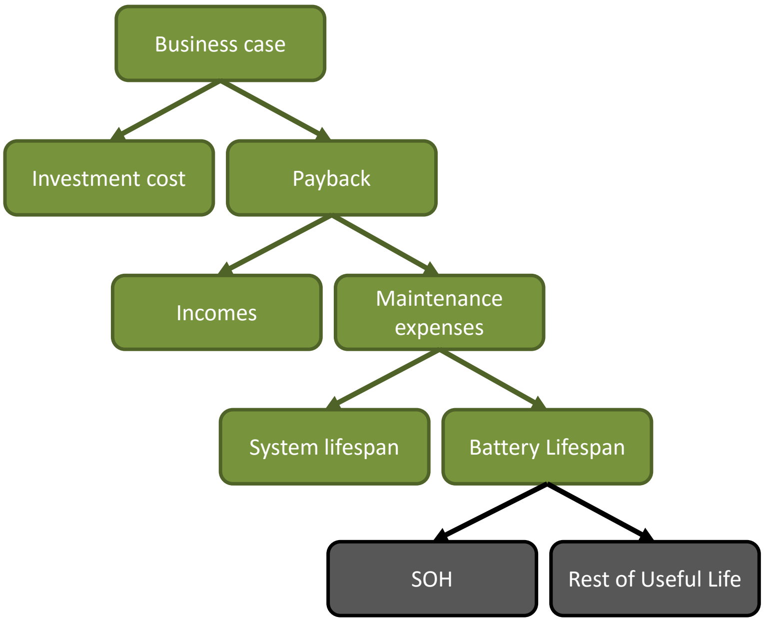


Figure 2.4: Business model analysis schema. It indicates that the determination of RUL and a good SOH assessment are the main research fields of this thesis.

In consequence, a good battery SOH assessment and a good knowledge of the RUL of the battery in every application is needed in order to prepare an accurate business plan. This explanation is visually described in Fig.2.4, emphasizing with darker colors the RUL and SOH assessment, whose determination is going to be the focus of research of this thesis.

Chapter 3

State Of The Art

"If I have seen further, it is by standing on the shoulders of giants.".

Isaac Newton.

3.1 Motivation

The expression: *"Standing on the shoulders of giants"* from Isaac Newton is a good metaphor of what this chapter is going to present.

In the following pages you'll find an state of the art, a look through the back mirror, to what other researchers have done before in the fields of energy storage systems, business and, particularly, in the aging of EV batteries. This will lead to understand the purpose and value of this particular thesis.

3.2 Energy storage systems

Although seemingly quite new, energy storage has been used for ages. For example, dams were firstly built to contain and store water, but also to run mills whenever it was necessary. Nowadays, hydraulic generator plants are responsible for most of the renewable energy used in the world [14] and pumped hydro systems are used for bulk power management services, pumping water back to the upper lake to generate electricity during peak hours.

The apparition of other energy storage systems, techniques and technologies, such as Flywheels, Compressed Air Energy Storage (CAES), batteries, etc. provide a wide range of alternatives to accumulate energy for an ulterior use [15]. However, as each technology has advantages and disadvantages, the selection of one or another alternative strongly depends on the final use of the stored energy.

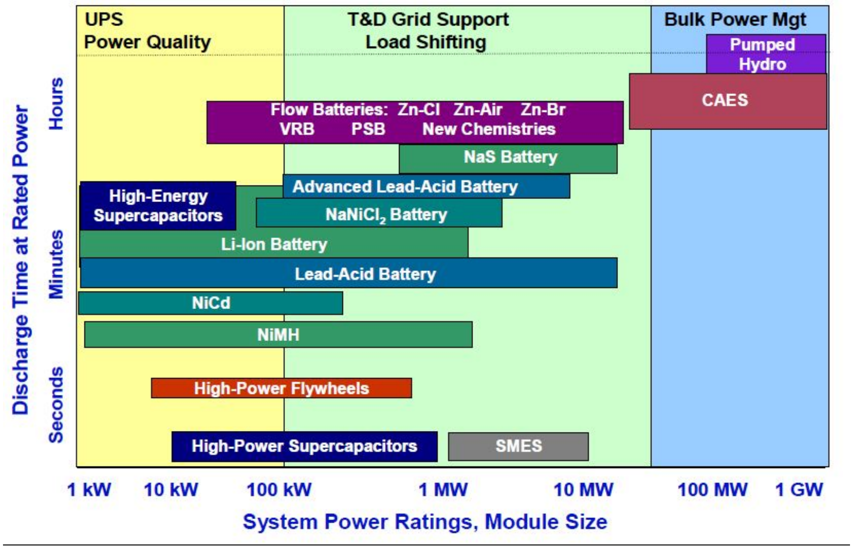


Figure 3.1: Positionning of Energy Storage Technologies.
Source: EPRI [16]

Grid services have two main parameters that define most of their needs: Power and duration. From this two main characteristics and considering investment costs and technology efficiency, a first selection of alternatives was done by the Electric Power Research Institute (EPRI) [16], which is presented in Fig.3.1. In this figure, the Power needs are presented in the abscissa while the expected duration of each service is found in the vertical axis.

From this figure it can be seen that capacitors, supercapacitors and Flywheels offer fast response services, while CAES and Pumped Hydro technologies are more oriented to high power services for longer periods, i.e. huge amount of energy, where fast response is not so crucial. In between, all type of batteries can be found, being Li-ion batteries the ones with a higher range of possibilities.

Combining the duration and power needs from Fig.3.1 and the different services presented in the previous chapter, the size of the storage energy services can be extracted. It is graphically represented in Fig.3.2.

Many different development and demonstrative projects have been and are being built to prove the value of batteries for energy and power grid services. Some examples of these type of projects using different battery technologies are [16].

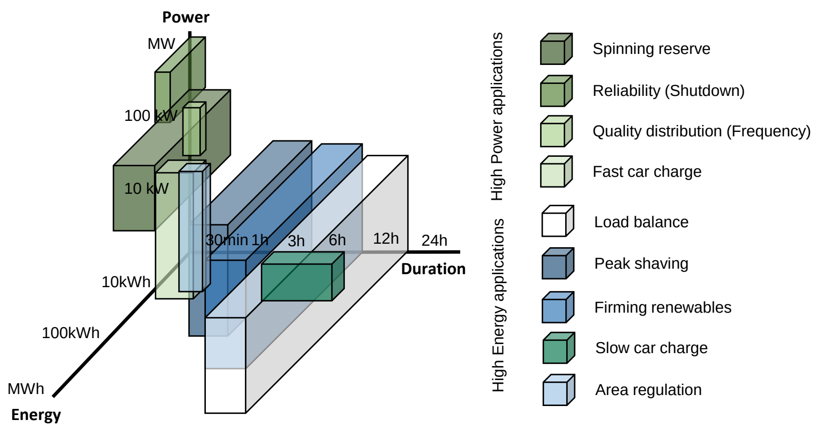


Figure 3.2: Power and energy requirements for different stationary applications

- The 12 MW frequency regulation and spinning reserve project at AES Gener's Los Andes substation in the Atacama Desert, Chile, using A123 systems' Li-ion power units (Hybrid-APUs^{TM}) [17].

- The 34 MW Rokkasho wind-stabilization project in Northern Japan, operational since August 2008 that uses Sodium Sulphur batteries.

- The Premium Power's 0,5 MW and 2,8 MWh TransFlow 2000 Transportable Zinc-Bromine energy storage system (to be tested by the EPRI and a utility consortium).

- The 5 kW and 30 kWh Prudent Energy project using Vanadium Redox batteries installed at Kitangi, Kenya, works alongside a diesel generator to compress a hybrid power system at an off-grid site.

- The first phase of the Ecoult 1 MW and 1 MWh Advanced Lead Acdid battery system at the Hampton Wind Smoothing Project in Australia.

Nonetheless, these classifications and mentioned projects were done considering new fabricated batteries. The idea of the Li-ion 2nd life batteries from EVs was yet not exposed. The cost of Li-ion battery was considered a major drawback for its selection in many cases and this led space for other technologies to participate. It has been during the recent years that many 2nd life battery projects appeared. As already mentioned in the introduction, the car companies are preparing joint-ventures or temporal alliances to run demonstrative projects using batteries from electric vehicles. Some examples are:

- The 4R-Energy joint venture between Nissan and the Sumitomo Company, that has done the bigger large scale storage energy system using 2nd life batteries, with 16 Nissan Leaf 24 kWh batteries in a wind farm in Osaka, Japan (Fig.3.3)[1].

Figure 3.3: Images of the demonstrator 4R-energy wind farm energy storage project in Osaka, Japan.

- The ABB and General Motors develop two second life projects. One using 4 PHEV batteries from the Chevrolet Volt to provide 25 kW and 50 kWh (Fig.3.4right)[2] and another one strengthening a solar and wind power plant (Fig.3.4left)[3].

[1] http://www.sumitomocorp.co.jp/english/news/detail/id=27673. Accessed 23/11/2015

[2] http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2012/Nov/electrification/1114_reuse.html. Accessed 31/07/2015

[3] http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/jun/0616volt-battery.html. Accessed 31/07/2015

Figure 3.4: First and second ABB-GM energy storage demonstrators projects in the US. The two images on the left correspond to the 1st project, the images on the right to the 2nd.

- The Second Life Batteries project is a consortium between Bosh, Vattenfall and BMW. It is still in the initial steps and it will try to re-use 100 BMW batteries from the i3 and ActiveE models by re-manufacturing the modules into re-build batteries. The demonstrator facility is expected to be built in Hamburg, Germany [4]. In Fig.3.5, the project schema is presented.

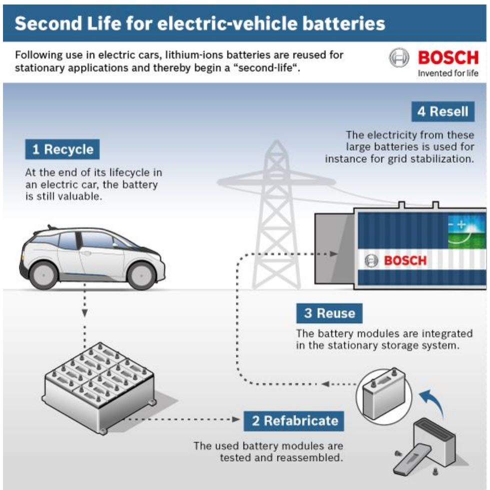


Figure 3.5: Second Life Batteries project schema to be build in Hamburg, Germany.

- The Department for Energy and Climate Change from the U.K. agreed to fund the Electric Vehicle Embedded Renewable Energy Storage and Transmission (EVEREST) project in November 2014 [5]. It is still at its first stages of development. Fig.3.6 presents the platform where it will be constructed.

Figure 3.6: EVEREST project platform in the U.K., with a container where batteries and electronic equipment will be installed and the solar carport and EV chargers

[4]http://www.bosch.fr/en/fr/newsroom_7/news_7/news-detail-page_60994.php . Accessed 23/11/2015).
[5]http://www.circontrol.com/circontrol-collaborates-everest-project-electric-vehicle-embedded-renewable-energy-storage-transmission/. Accessed 23/11/2015

- The Greendatanet project is funded by the European Union and re-uses Nissan leaf batteries to provide energy support to data centers building three pilot plants in Switzerland, France and Netherlands (Fig.3.7).

Figure 3.7: Logo of the Greendatanet project

- The joint demonstration project for utilizing used lithium-ion batteries from electric-powered vehicles was announced on July 10th 2015 by Mitsubishi[6]. The project will be executed by partnership between Electricité de France (EDF), Forsee Power, a key provider of energy storage solutions sponsored by EDF, and PSA Peugeot Citroën. The demonstration project was inaugurated in September 2015 at Forsee Power's new headquarters near Paris (France). The purpose of the project is to demonstrate efficient and economically feasible energy management practices based on the optimization of electricity storage, charging and generation technology with respect to existing demand. Fig.3.8 presents an schema of the project.

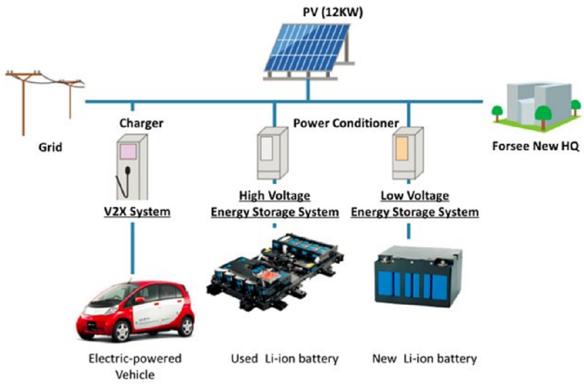


Figure 3.8: Batteries Second Life Project Schema

- The last announcement was done in November 2015 by Daimler. The *E-mobility thought to the end* project plans to build the 2nd biggest energy storage facility using EV's Smart batteries. It is a cooperative project between Daimler, The Mobility House, GETEC and REMONDIS. The plant will be capable of storing 13MWh according to the announcement [7] and will be located in Lünen, Germany (Fig.3.9).

[6]http://www.mitsubishi-motors.com/publish/pressrelease_en/corporate/2015/news/detailf710.html. Acessed 31/07/2015

[7]http://media.daimler.com/dcmedia/0-921-614306-1-1861874-1-0-1-0-0-1-12639-1549054-0-1-0-0-0-0-0.html?TS=1447166558769. Accessed 23/11/2015).

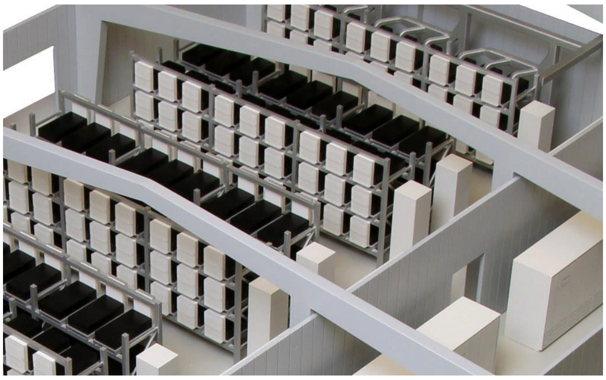


Figure 3.9: Rendered interior of the expected energy storage facility by Daimler, with many shelves of re-manufactured batteries

- Finally, the Generalitat de Catalunya partially funded in 2014 the Sunbatt project. This project deals with 4 PHEV batteries offered by SEAT to provide a maximum power of 40 kW power and a total amount of energy of 25 kWh. Fig.3.10 shows the installation environment, with a solar carport, 4 EV chargers and the container where the power electronics and the batteries are placed. Part of this PhD thesis is based on this project.

Figure 3.10: Sunbatt project demonstrator at SEAT facilities in Martorell, Catalunya, Spain. Left: Entrance to the container where batteries are stored. Right: Rest of the installation, with the solar panels, the chargers and the container in the back.

3.3 The Sunbatt Project

As the thesis is somehow involved in this project, an special section is dedicated to describe it.

This project pretends to demonstrate that Volkswagen PHEV batteries are available for stationary applications. It uses these batteries to store solar energy that will be used afterwards to charge EVs, to offer different services to the local electricity grid and as a transportable energy storage system.

To do so, four 8.8 kWh PHEV batteries are placed in a maritime container. These four batteries are connected, by relays, to two 20 kW AD/DC converters. The idea of the maritime container is taken from the requirement that the demonstrator should be transportable and capable of working in other installations. Taking into account that the container is placed in the open air, it would heat up easily when the Sun is up. Hence, for security and safety issues, the container is equipped with a cooling system and the batteries are installed with their refrigeration system, extracting the air to the outside of the container. In order to reduce the use of the cooling system, which consumes energy without providing any added value, the container was thermally isolated in the ceiling and walls.

In the CTS (Centro Técnico SEAT) installations, the Sunbatt container is connected to the

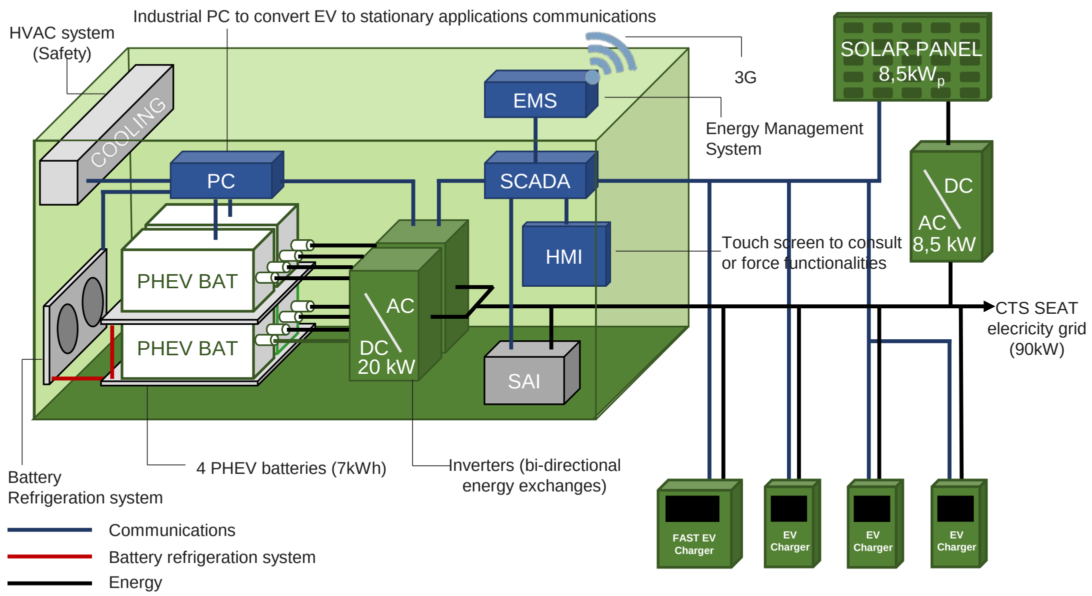


Figure 3.11: Sunbatt project Schema, showing the power and energy paths (black lines) and the communications between elements (blue lines).
Source: Gibert et al.[18]

grid, to 8,5 kWp photovoltaic panels in the carport, to 3 normal 3,5 kW car chargers and to a 50 kW car fast charger, as it is visible in Fig.3.10.

To facilitate the comprehension of the required equipment, an schematic presentation of the container is presented in Fig.3.11.

Apart from the mentioned power electronics, which are connected by black lines that define the energy distribution, there are other elements inside the container. These elements form the communication, security and control system and are connected by a blue line (Fig.3.11).

The PC connected to the batteries works as a Gateway. It translates the vehicle CAN messages into comprehensible CAN and Modbus TCP messages to the rest of the system. Additionally, it sends back to the batteries all the messages they expect from a car. A deeper explanation of the communication system will be exposed in **Chapter 5**.

Then, this PC is connected to the SCADA. The SCADA is the steersman, the element in charge to give the orders to all the equipment and to receive the working information. However, it is connected to the Energy Management System (EMS), which is the captain. The EMS is in charge of calculating and optimizing the energy flows in order to reduce CO_2 emissions and the energy bill at the end of the day. This EMS is also connected to weather forecasting services and to electricity utilities. Finally, the last element to introduce is the touch-screen or HMI (Human Machine Interface). The system could work without this element but, as it is a demonstrative project, it is intended to work also as a showroom and to force some specific working modes.

The Sunbatt project started to work when this Thesis was almost finished, thus, no validations or functional information could be retrieved from it. However, it was very useful to understand the transformation needs for batteries and the communication difficulties.

Now that it works, it can be the perfect departing point for further research studies and validations.

3.4 Lithium ion Batteries and aging

If Li-ion batteries were already tested in demonstrative projects showing good performances, how is it that so many 2nd life battery demonstrative projects appeared? This sections will try to answer this question.

It is important to delve into the knowledge of the aging phenomena that occurs on Li-ion batteries to understand the implications of a first and a second life.

Generally speaking, the terms "Lithium" batteries or "Li-ion" batteries define a type of battery that uses the Lithium ion as the instrument to transport the electron from the anode to the cathode and vice versa. However, there are many different elements and chemistries used in the anode, cathode, separator and electrolyte forming many battery alternatives.

This variability provides a wide range of performance characteristics. For example, Lithium Cobalt Oxide (LCO) and Graphite have high power density but are more unstable, on the contrary, Lithium Titanate (LTO) batteries are much safer and last longer. More detailed explanations of the different options will be assessed in chapters 4 and 12. Nonetheless, the batteries used in this study have Graphite and Lithium Nickel Manganese Cobalt Oxide (NMC) compounds for the anode and the cathode, which are the most common Li-ion battery type in the automotive industry [19].

This variability has also an important effect on battery aging, which evolves differently depending on the chemistry [20] and even with the same type of batteries the aging is no equal for all cells, having a growing dispersion along with its use [21]. There are many different studies regarding battery aging, being the reviews from [22] and [23] some good examples of what has been done regarding the aging of batteries. The most relevant parameters that are used to determine battery aging or SOH are:

- The loss of capacity.
- The internal resistance increase.

Battery aging occurs during energy exchanges and also when it is stored. This means that even when the battery is unused, internal degradation continues. In order to determine how this degradation occurs, two type of tests are followed to accelerate the aging phenomena: The calendar and the cycling aging tests [24], [25].

These tests and studies contributed to determine the basic factors that affect battery aging, which are:

- SOC: The State Of Charge (SOC) defines the level of activity inside the cell, at higher SOC, the battery electric material is more active and the internal resistance is lower. However, this higher level of activity accelerates the aging of the battery. Hence, higher SOC rates implies lower lifespan.
- Temperature: Similarly to SOC, the internal activity of cells increases with temperature and, correspondingly, so does aging. Higher activity causes faster and undesired side reactions such as anode deformations, gas formation, Solid Electrolyte Interface (SEI) cracks, etc. [26]. On the contrary, at low temperatures the activity is reduced and lifespan increases substantially. Yet, temperature has other details to take into account. When going below 0^{o}C, the cell internal resistance increases dramatically and consequently, the usable capacity drops noticeably. Additionally, Lithium platting may occur at these temperatures, which accelerates the battery aging in a mode not usual otherwise as there is less and less active lithium in the cell. On the contrary, higher temperatures derive in instability, cells may start an exothermic reaction that may end up with an explosion or burn [27].
- C-rate: The C-rate expresses the intensity of current going through a battery. It is defined as the nominal intensity that would discharge the cell in an hour. That is, a 1C discharge

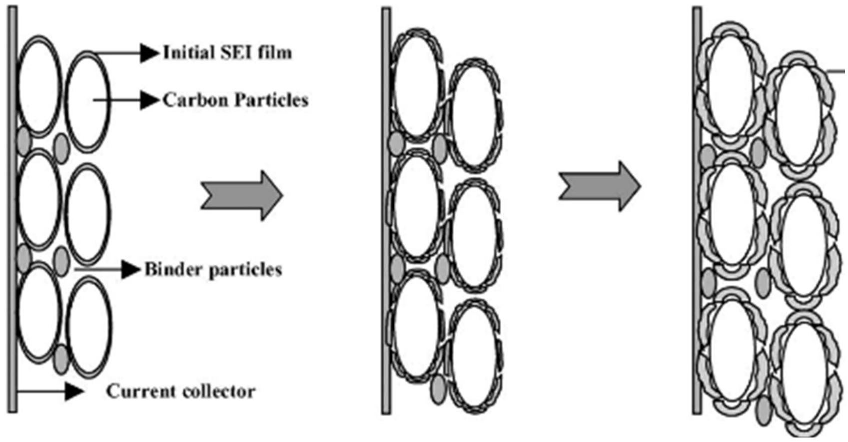


Figure 3.12: Representation of the SEI growth.
Source:Balbuena [28]

rate for a 25 Ah cell would mean a discharge of 25 A. Again, higher C-rates accelerate the aging mechanisms.

- DOD: Higher Depth Of Discharge (DOD) evolve also in an acceleration of the aging mechanisms. That is, batteries cycling at 10% DOD will be able to exchange more energy than batteries doing 80% DOD cycles.

These 4 factors activate or enhance some physical transformations and side reactions inside batteries, which end up with an acceleration or deceleration of the aging phenomena. A short description of what may occur inside the cells is presented below:

- SEI growth: Normally, it is considered that cycling is the main cause of aging. In fact, what occurs each time a cell cycles is that some of the active material is deployed in the interfaces of the anode forming the SEI. This layer protects the anode but it also has negative effects on the battery performance. It is formed by lithium salts and other elements. This lithium captured to form the SEI is not further available for electron transportation from the anode to the cathode being one of the causes of active lithium loss, thus capacity loss. Moreover, this accumulated material complicates the intercalation of ions, increasing the internal resistance of the battery which evolves in a loss of power. A representation of the SEI growth is presented in Fig.3.12.

  The SEI behaviour is similar to that of copper oxide layer that grows, protecting the metal inside, until a point of stabilization. But in the case of batteries, small parts of SEI detachments occur due to the high C-rates and temperature continuing with the uninterrupted SEI growth. This effect is also found in the cathode in a softer mode. In this case, it is called SPI

- Anode deformation: As already mentioned when describing the effects of temperature and C-rate, the higher the C-rate the more active battery materials are. The dynamic behavior is accelerated and the intercalation of lithium ions becomes rougher. It may happen that lithium ions drag solved particles deforming the anode. This will hinder future intercalations.

- Lithium plating: This phenomena occurs, generally, during charges at temperatures below 0°C or at discharges below the minimum established SOC limit. However, it has been found in many other cases in a softer degree. Lithium reacts forming metallic compounds between the anode pores, affecting future interchanges. With time, oxidation will gradually grow moving through the electrolyte.

- Binder corrosion: The anode and cathode are equipped with a binder, normally made of Copper, which collects the electrons from the Li-ion intercalation. Over-discharges may cause corrosion evolving in an internal resistance increase.

- Separator perforation or puncture: Corrosion from the binder and the metallic Lithium makes growing and moving dendrites that may eventually puncture the separator. This will instantly cause a short-circuit that may not be controlled and that may eventually finish in a burning cell or battery. In fact, the inherent cell activity makes it really difficult to stop a fire in a battery, as it is an exothermic reaction that does not need Oxygen to burn (Fig.3.13 [8] [9]).

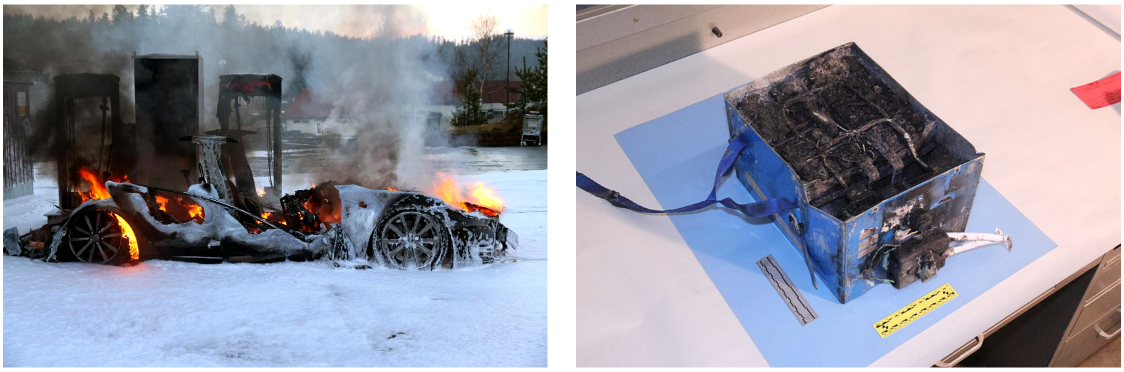


Figure 3.13: Left: A Tesla Model S burns while charging in Norway; fireman could not stop the flames. Right: Boeing 787 Dreamliner's Li-ion battery that burned up due to a thermal runaway.

- Gas formation: In some of the Li-ion chemistries, gas liberation may occur by storing batteries at high temperature. This gas is formed by active material, which causes a loss of capacity.

Fig.3.14 presents an schematic overview of the different factors that have some effects on battery performance together with their related effects and consequences on the battery behavior.

Many factors have many effects and converge in different consequences, so it is not simple to determine the exact cause of a battery failure.

Although most authors agree with the aforementioned battery degradation mechanisms [29], [22], [23], [30], [26], [6], [31] there is a wide dispersion of test results having cells that achieve the 80% SOH in 300 or 3.000 cycles [24], [32], [33], [34], [35].

This fact, together with the constant innovation in cell chemistries, additives and manufacturing processes, makes it impossible to accurately predict the aging evolution of new cells without doing a sequence of tests to extract the aging parameters.

Car manufacturers warrant 8 to 10 year or 100.000 to 150.000 km battery lifetime. They have done lots of aging tests in their installations on their particular cell chemistry to guarantee these values.

The cycling and calendar aging tests are very time consuming ranging from 50 days to 3 years [36]. Considering that these tests have to be done in climate chambers and that they need an electric and electronic equipment fully dedicated to the tests, it is clear that they are also very expensive. This is why most of the executed tests finished when the cells reached the 80% SOH and did not continue forward [37], [38]. Thus, not many studies go further in the RUL analysis for 2$^{\text{nd}}$ life battery applications, being still something unknown.

[8] http://www.chicagotribune.com/classified/automotive/ct-tesla-fire-supercharger-norway-20160104-story.html Accessed: 10/01/2016

[9] http://www.bbc.com/news/business-21054089 Accessed: 22/01/2016

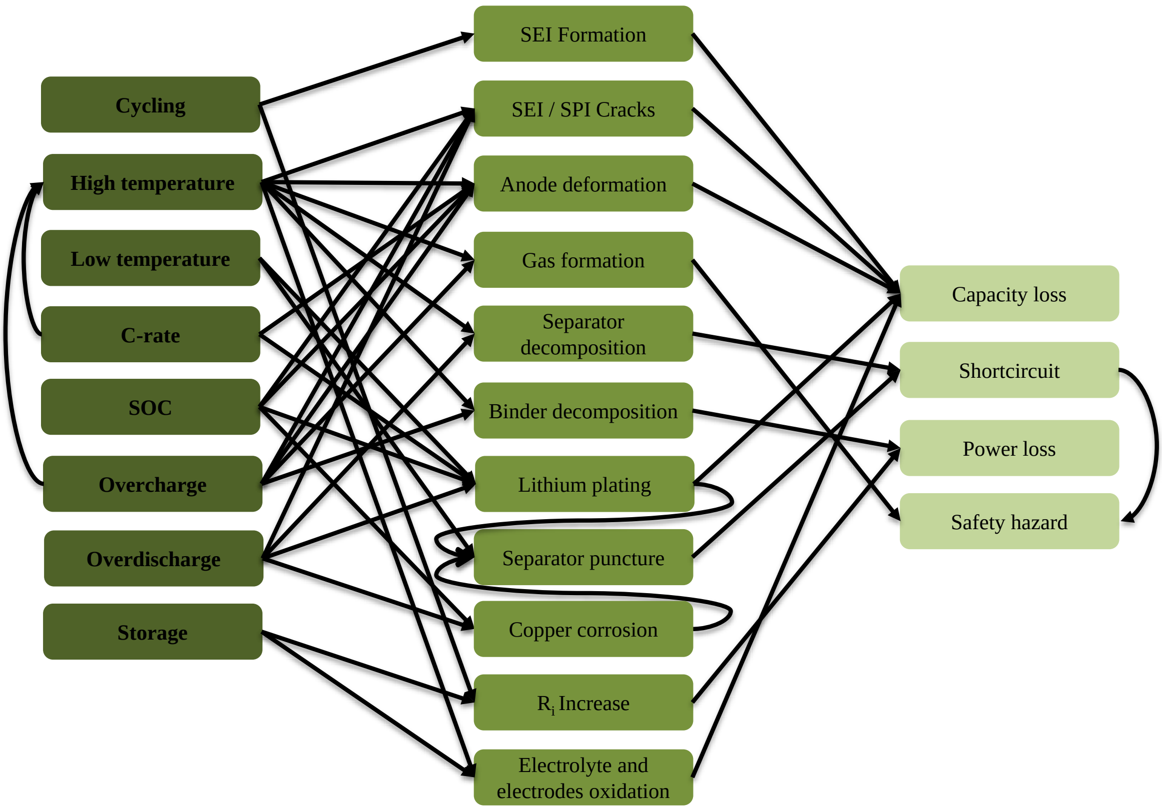


Figure 3.14: Representation of the relation between the factors effects and consequences which take place in a battery system.
Source: Canals Casals et al.[8]

Additionally, it has been observed that, at certain point, battery aging is noticeably accelerated. This is called sudden death [21]. Up to now, nobody knows exactly when this may occur[10]. Will it be during the second life?

3.5 Aging and second life studies

The first aging studies on batteries' 2^{nd} life appear for the need of having a base for economic calculations, not from a technical point of view. Aging studies on batteries' 2^{nd} life try to determine the RUL for each application, which are still unanswered questions (Fig.3.15).

The first economical approaches determined the RUL with rough and superficial methods:

The economical approach followed by Heymans et al. [39] was based on a Chevrolet Volt battery. Although the study recognized that there were many different aspects concerning the battery lifespan, the authors of the study directly assumed that it would last 10 years to loose an additional 20% of its capacity doing daily cycles for household applications.

Lih et al. [40] used a similar approach. They considered that the total lifetime of a battery was fixed at 15 years and economically calculated that, from an economical perspective, the best moment to collect EV batteries was after 3 years. Similarly, Viswanathan & Kintner-Meyer [41] calculated the best moment for EV battery removal under several 2^{nd} life applications.

[10] An interesting video by professor Jeff Dahn from the Waterloo Institute for Nanotechnology describes interestingly how to postpone its appearance https://www.youtube.com/watch?v=9qi03QawZEk

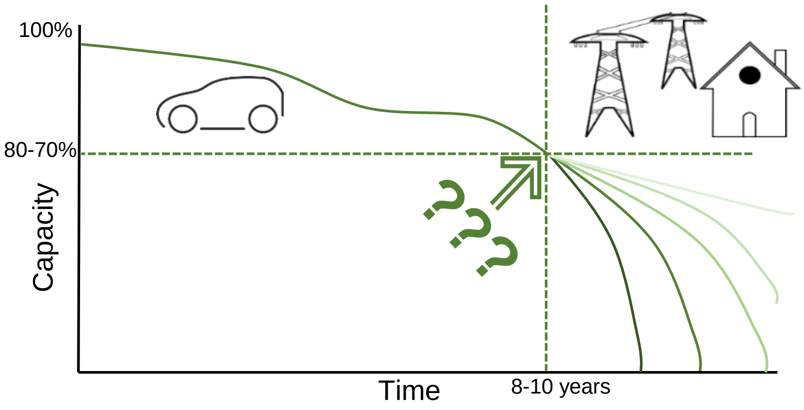


Figure 3.15: After the 1st life in EVs, the expected RUL for batteries in 2nd life applications is still unknown.

Ciccioni et al. [42] used the expected lifetime based on the number of cycles of a 30 Ah EV battery capacity. They considered that a battery for stationary applications started with 20 Ah, therefore, its End of Life (EoL) would be when the capacity achieved 16 Ah. Thus, if the end of the 1st life in EV was achieved when the battery had 24 Ah, it could still do 1300 cycles before reaching the final EoL. It can be noticed that this study did not took into account the different aging factors, neither the 2nd life requirements and battery loads.

The economical approach followed by Cready et al. [43] used the expected energy throughput based on the remaining complete cycles after the 1st life in EV.

Still based on the remaining number of cycles for 2nd life applications, Strickland et al. [44] divided the nº of cycles by the DOD in order to know the expected RUL for each application.

P. Wolfs [45] studied the second life degradation and obtained a linear response at 25ºC, ºC and 100% DOD cycles. This correlation was used in his study even-though he assesses that there are other degradation factors that should be taken into account in further studies.

One of the most active authors studying the second life of EV batteries is J. Neubauer. He did many research reports and papers working in the National Renewable Energy Laboratory in the US. His first economical approaches considered a total lifetime of a battery of 20 years and divided them in 15 years in a vehicle and 5 for 2nd life applications [46], [47]. More recent studies are based on the Battery Lifetime Analysis and Simulation Tool (BLAST) that he developed. BLAST incorporates two options: a simple energy accounting model and a zero-order equivalent circuit model. The Capacity fade was calculated including the calendar and the cycling aging (considering DOD, Temperature and voltage) [48], [49].

Based on empirical results, Penna et al [50] considered a linear regression of the SOH evolution adding an uncertainty factor.

The quantification of the economic benefits of second life batteries in smart grids done by Debnath et al. [51] was done using a semi-empirical model. They considered a calendar life plus a constant cycling degeneration rate at constant room temperature. However, they introduced a DOD correction.

Keeli & Sharma also introduced the DOD and the C-rate effect. However, they did it based on the Capacity loss rate under the specific 2nd life conditions studied, that is, these parameters should be recalculated if the DOD and the C-rate change.

The study done by Hamidi et al. was a little more complex. The capacity fade was simulated using a circuit equivalent electric model, which will be described in the following section, and not just mathematically calculated based on two assumptions. However, the approach was simple. They considered a 3.600 full cycle lifespan and evaluated aging using the number of cycles and two correcting factors based on the temperature and the C-rate of the 2^{nd} life application.

As it can be observed, the RUL approach for 2^{nd} life applications is becoming more complex and accurate, adding new parameters and incorporating some of the aging factors to adjust the results to reality. However, not many of them are using computational models to determine RUL.

3.6 Aging battery models

To reduce the cost and experimentation time for RUL determination, the use of computational solutions was developed. These computational solutions try to simulate the battery performance and functionality providing faster results and conclusions, so there is no need to really build the testing equipment or wait 10 years to see the battery degradation. There are several battery models based on different parameters or physical reality to estimate the RUL at different battery loads.

- *Physic-chemical or electrochemical models*: These models are based on the real internal reactions of the batteries and on the study of the effect of degradation mechanisms on the battery components. These models have a detailed cause-effect explanation and might turn into a good comprehension of the battery failure [52], [53]. However, they are very complex and they have a high computational cost, deriving in not so cost-effective results.

- *Electric equivalent models*: These models are based on the electric response of the battery. They are built with simulated electric elements, such as resistances, capacitors, power sources and inductance among other elements. They are commonly used to see how an electric system respond with the incorporation of a battery. The degradation mechanisms can be introduced using simple mathematical expressions that modify the parameters of the electric components in accordance with the accumulated inputs (such as current or Temperature). These models are simpler, with a lower need of computational calculations and they can offer faster results. However, they provide no explanation of the degradation modes or the failure causes. They can be very simple, like the zero-order equivalent circuit model used in BLAST [48] (with just one resistance), a little bit more complex models using series of Resistance and Capacitator (RC) in parallel, adding an inductance or Warbburg impedance [54].

- *Using mathematical tools*: This type of models can be introduced somehow in the rest of models. They treat the battery as a black box and use different mathematical tools, such as particle filters [55], [56], neuronal area networks [30], fuzzy logic [57], [58] or support vector machines [59], [26] to calculate the response, effect or whatsoever it has been mathematically modeled inside. Most of them need lots of data and may need important computational power.

- *Statistic models*: These models are mostly used for prognosis purposes. They are based on real data collected from the application and use specially developed algorithms to predict the evolution of the desired parameters. This type of model usually take advantage of the mathematical tools previously mentioned, hence, some of them can "learn" or may be able to compare the results with previously gathered information (from experimental tests or from other real use applications) [26], [56], [60], [61]. Their outputs are constantly evolving obtaining more and more accurate results as new data is incorporated. They are commonly used for useful prediction applications, such as expected driving range before recharging the battery.

All of them have been used for battery RUL estimations, mostly under EV conditions and until they achieved the 20% capacity loss. In this study, the electric equivalent model will be used for RUL estimation.

Electric equivalent model

Electric equivalent models are intended to provide the same electric response as the simulated electronic device. In this case, a battery.

All battery models have something like an ideal source, it provides the Open Circuit Voltage (OCV) curve that defines a battery. This OCV curve relates the SOC and the stabilized voltage on battery borne. For a correct OCV characterization, the stabilization period should be longer than 30 minutes. The longer the resting period, the more accurate the OCV curve will be. Each cell type has a particular OCV curve.

The next most common electric element introduced in electric equivalent models is a simple resistance. It simulates the instant voltage behavior of a battery. It is the element that simulates the initial voltage drop of a battery under current pulses or changes. This voltage drop is mostly caused by the internal resistance of the battery. It is used when fast computation and easy modeling is needed.

However, this is not the only voltage variable. As it can be seen in Fig.3.16, there is effectively an initial step down when the current pulse begins. But the voltage continues decreasing while the battery discharges and, on the contrary, it increases while charging. This slope changes depending on SOC (because of the OCV curve), temperature and current rate. That is the reason why battery tests should be done under the same conditions.

Before achieving the constant slope appreciable in Fig.3.16 from second 10 to 28, there is a transition period. This transition might be faster or slower. Again, there are many factors altering this response: Temperature, previous battery load, aging, etc. More details of the battery voltage response and behavior will be assessed in Chapter 7 that deals with SOH estimation based, specifically, on the voltage recovery. Nonetheless, it is introduced here to explain the other elements that can be used for electric equivalent models.

Normally, a fast voltage transition period (less than 2 seconds) is achieved by adding a resistance and a capacitor in parallel in the circuit. Then, to improve the accuracy of the simulation response, additional RC pairs can be added in series [10].

Simple cell characterizations can be done just doing pulse and capacity tests. However, the best way to characterize them is using the Electrochemical Impedance Spectroscopy (EIS). This method analyses the response of the battery to AC current in a large range of frequencies. This

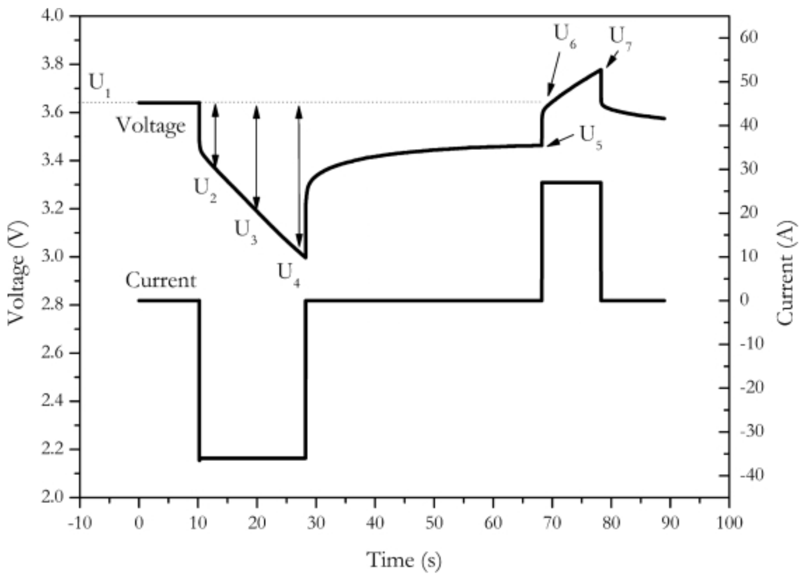


Figure 3.16: Voltage response to current pulses.
Source: Schweiger[62]

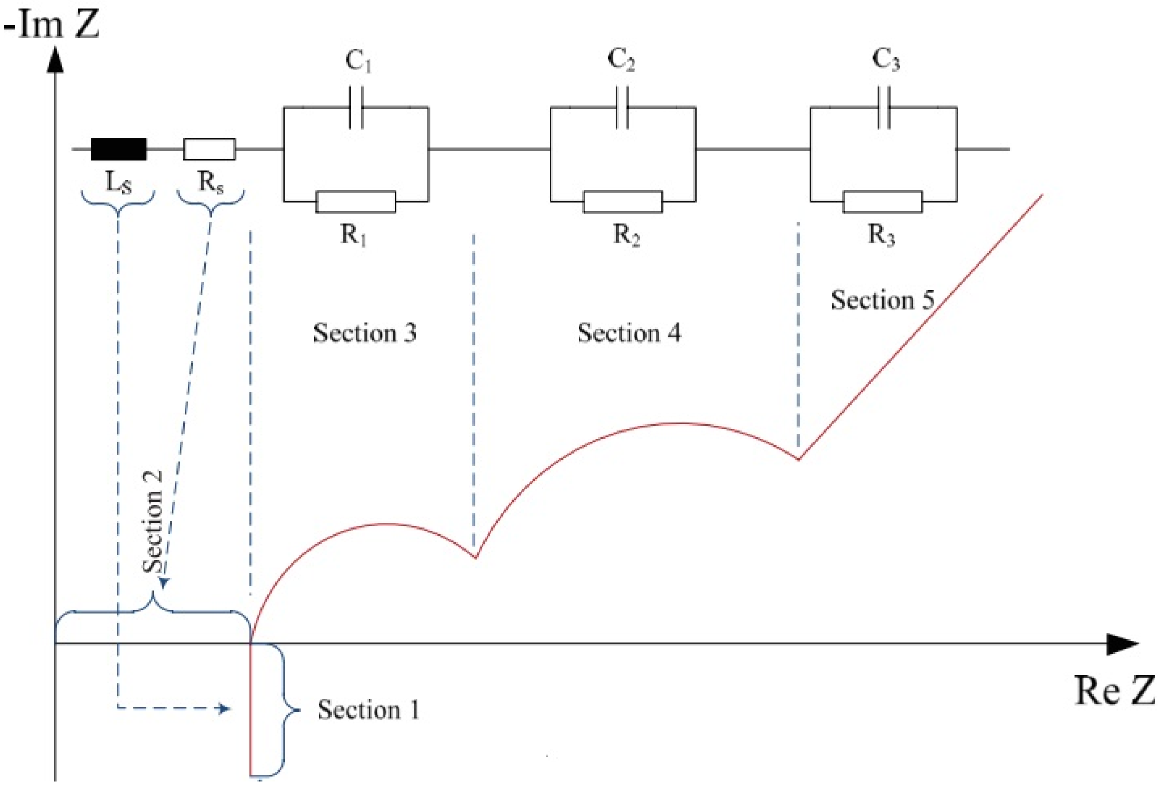


Figure 3.17: Typical Nyquist plot for a Li-ion battery and the corresponding equivalent electrical circuit.
Source: Storage Systems based on Electrochemical Batteries for Grid Support Applications [63]

testing provides a Nyquist plot that will be used to identify the elements in the circuit and characterize them. Fig.3.17 visually defines what is represented by each electric element in the circuit. I can be observed that the inductance is related to Section 1, that the resistance displaces the whole curve to the Right and that the subsequent RC pairs are responsible of the semicircular forms observed.

More improvements are introduced to depress the semicircular form of the Nyquist plot. The Constant Phase Element or ZARC element is used in some studies as it provides the best response results. A good explanation of the different electrochemical models can be found in [54] and [64].

Of course, all these explanations and testing are done for each temperature and SOC state in order to fully determine and characterize a battery. Hence, a good battery characterization can take months or years to be prepared.

In the electrochemical models, the values of these components forming the electric equivalent

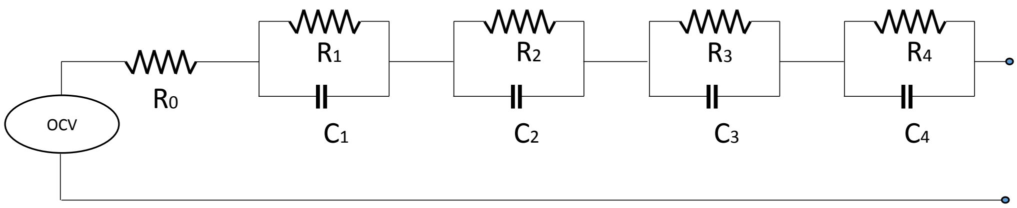


Figure 3.18: Electric equivalent circuit used in this thesis with a resistance and four RC pairs in series.

circuit are introduced with the aid of look-up tables. This look-up tables have the battery parameters obtained for each Temperature and SOC state. Thus, when the model runs at a certain temperature and SOC, it searches into the look-up tables the corresponding value. Some models use also the C-rate as a modifying factor [54].

For this thesis, the selected electrochemical model consists in a resistance and 4 RC pairs in series as the one presented in Fig.3.18. The functional parameters of this model were characterized in the Volkswagen installations using the EIS methodology.

In this study, the aging of the battery will be introduced into this model.

3.7 So, what is new then?

As it has been described, aging models have been introduced and deeply developed to reproduce the aging evolution of a battery under a wide range of accelerated aging conditions.

The calendar aging at high temperatures is maybe one of the most studied cases. Then, hundreds of cycling models have been developed combining DOD, C-rate and temperature, which provide such a vast quantity of results that it is hard to find a clear tendency. A deeper description of the developed model is found in chapters 8 and 9. These chapters explain how the parameters and equations used for the aging model were selected and developed in this thesis.

But, as stated previously, many models where just explaining the aging phenomena under precise conditions, but they were not ready to correctly respond to other applications. Other had a wider horizon and were used in vehicle environments to predict a car life, to determine the best way to charge an EV [38], [65], to show how the benefits of intelligent battery charging [66] or to describe the possible battery life alterations when applying ideas such as the Vehicle To Grid (V2G)[67], [68].

Finally, a handful of works analyze battery aging for other applications, such as to provide energy support to wind or solar power plants [54], [64].

In all these cases, aging was observed from a 1st life perspective. The 2nd life battery aging evolution is not yet fully studied and, what is more important, the different energy loads have been manly evaded, which may cause a huge difference in the final RUL for each application.

Al along this thesis, several 2nd life applications will be presented. Their functional load requirements will be introduced in the aging model developed specially for battery aging in 2nd life applications obtaining a resulting RUL for each application. Up to twelve different cases will be simulated based on 6 general cases that will be addressed in more detail in the following chapters, which are:

- Fast EV Charge: Three different cases will be studied. A first simulation will consider only two charges per day. The second one will consider the batteries as Peak Shaving support. The last case considers and uninterrupted charge-discharge cycle.

- Self-consumption (or Load balance): Two cases will be analyzed. The first approach will consider constant current demands, while the second approach will be adapted to the production of energy solar panels generation.

- Island installations. Only one study case will be done for this application with constant demand response.

- Area Regulation. The study of this application will be find in three cases. The first case analyzed departs from the second self-consumption approach, adding the real Area regulation current profile in it. The other two cases should be considered as a constant cycle added to other two functions: the Uninterruptible Power Supply (UPS) and the Self-consumption on a simplified profile.

- UPS or Shutdown emergency services: Two cases are analyzed. The first case studies this service alone and the second, as mentioned in the previous point, studies it together with the Area regulation.
- Transmission Deferral: One simulation will be done taking real data from the electricity grid demand.

Chapter 4

Needs for battery reuse

"Furiosamente apegados a la vida, retozamos en la avanzada juventud, como si la muerte no existiera."

Gioconda Belli *"La avanzada juventud"*.

4.1 Motivation

This chapter should be understood as an overview of the EV batteries' reality and a nearing to the diversity that nowadays is found in the EV market while proposing some strategies to face it. Therefore, it is more a technical than a scientific approach as it studies the battery reuse from a practical and not only from a theoretical point of view.

What is needed to know, for EV batteries to be reused, is to understand the transformation, communication and other technical issues that should be taken into consideration before batteries are usable for 2^{nd} life applications.

This Chapter starts with an introduction of the EV market diversity and how batteries could/should be collected. Afterwards, it analyses the major differences to consider in the reuse of batteries from EV models, such as the cell form, chemistry, functional limits, modules, power, capacity, Battery Management System (BMS), communications and packaging. This chapter continues with the introduction of some management solutions to face this battery diversity, which are: specialization, selection or use all the available batteries together. It finally concludes that, from all the presented solutions, the one that is being majorly followed is the specialization by joint ventures between car manufacturers and electricity grid enterprises. It also highlights the relevance of faster SOH assessments to reduce the cost of the battery re-manufacturing. This last aspect is going to be analyzed in further detail in Chapter 6 and a new proposal of SOH assessment is exposed in Chapter 7.

This chapter is based on the poster presented at the 1st Energy Systems Conference: When theory meets reality, that took place on June 24-25, 2014 entitled: *A review of the complexities of applying second life EV batteries electric car batteries on energy businesses.*

4.2 Introduction

Many EV projects appeared in the last decade in the UE. As an example, during the last years in Spain, licenses were given to 18 different models from a total of 15 car manufacturers (Fig. 4.1), showing that electric mobility is clearly entering into the market [4] and it is expected to capture a relevant part of the market even in the worst scenarios [69]. However, the EV has some drawbacks to overcome, like the price and the short autonomy range [70].

Indeed, the EV entrance into the market is environmentally envisaged, but it also comes with threats and challenges for the electricity grid and infrastructure. The fast charge, the peaks of electricity consumption, the charging points distribution, the local service transformers overheating and the risks on secondary service lines are just a few of these future problems to be solved [71], [72]. Fortunately, the energy storage systems are often presented as possible solutions to these problems, providing services like load leveling, peak shaving, frequency regulation or sudden shut downs among others [73].

Since now, batteries were not considered for grid services for several reasons. A major handicap was the advances in the state of technology, now that Li-ion batteries are reaching good performance results, it is their high price that impedes their entrance into ancillary grid services.

Three key factors work to help batteries economic competitiveness:

- New Li-ion batteries are experiencing a considerable and sustained price reduction because of increasing mass production. It is expected that prices reduces to half within the next ten years [74].
- The continuous electricity price increase.
- The future availability of EV batteries ready to reuse, which is the subject of this chapter.

It occurs that EV batteries are considered not useful anymore for traction purposes after they have lost a 20% of its capacity and they should be retired from the car. Then, as these batteries still have an 80% of its initial capacity, they could possibly be used as the energy storage system for the aforementioned solutions [43]. Therefore, what was a problem from the car point of view could be looked as an opportunity from the electric services side. In fact, some companies are

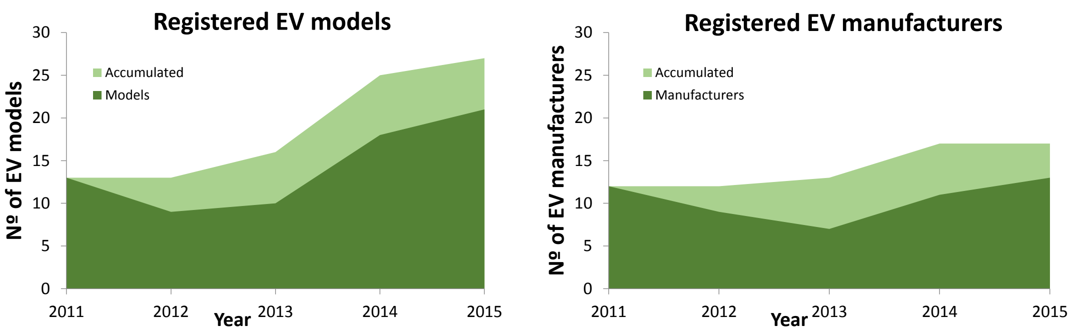


Figure 4.1: Evolution of the EV models licensed in Spain (Left) and evolution of EV manufacturers (Right).
Source: ANIACAM (Asociación Nacional de Importadores de Automóviles, Camiones, Autobuses y Motocicletas)

trying to demonstrate their performances and functional benefits with diversity of projects even though the first approaches do not point towards huge revenues [75]. This is when the circular economy and the 2^{nd} life of battery management enter into play.

In this study, the different aspects involved with the reuse of EV batteries and the ways to confront them are presented, making special attention to the main points that should be taken into account before starting up one of these business.

4.3 Battery collection

The first point to take into consideration is the origin of these batteries. In fact, used EV batteries do not come from a factory as most products normally do; they come from old cars spread all over the world. Therefore, the collection of batteries from old cars is something to deal with. Cars should normally finish their lives in Authorized Treatment Centers (ATC), where they are going to be dismantled. Some parts will be sold as spare parts, others will be recycled and the batteries should be sent to the re-manufacturing plant. Hence, an agreement with car manufacturers or ATCs should be done.

An important issue to consider is the inherent danger when working with batteries. A discharged battery is not a battery without energy inside. Indeed, batteries have security voltage limit to ensure a stable working range. So, when an EV battery is discharged it still has more than 230V and plenty of power and energy to deliver. Additionally, it is impossible to know its SOC without electronic equipment. Therefore, safety is a must when manipulating these items. EV batteries normally use Li-ion to transport the electrodes from the anode to the cathode and vice versa. Lithium is a very reactive element and it is another reason that helped to classify this type of batteries as dangerous goods [76]. This classification causes a non-trivial transportation and packaging, detailed in [77], [78], that should be taken into account when calculating transportation costs and equipment required.

Additionally, it is important to identify who is the final responsible of this battery. The European directive 2006/66/EC states that a company putting a battery into the market is responsible of its management at the end-of-life. In the case of EVs, it corresponds to the car manufacturer. However, when dealing with EV batteries' 2^{nd} life, it is not clear where the responsibility falls to because the battery was already in the market. Hence, this issue should be regulated by the corresponding institutions on each country.

The easiest way to proceed with the battery collection would be if it is carried out by the car manufacturer. Nonetheless, as car manufacturers have contracts with the Integrated Management Systems (IMS), companies in charge of the component waste management, it could be one of these companies doing the collection. The final solution would come from the remanufacturing company, which could do the management after registering itself as an IMS and seal an agreement with car manufacturers and ATCs.

4.4 Battery variability

The next barrier to deal with is the diversity between batteries. As presented in Fig. 4.1, there are plenty of electrified models from almost all car manufacturers. Indeed, most of the car brands have a partnership or specific agreement with battery manufacturers. Moreover, each battery manufacturer is specialized in certain type of cells and designs them to fulfill the requirements provided by the car manufacturer. In addition, these requirements strongly depend on the car model performances. Consequently, there is a vast rainbow of possibilities concerning the different aspects of batteries to be assessed. Table 4.1 shows the characteristics of some electrified models confirming this variability. The different aspects to consider between EV models are: the cell chemistry, the functional characteristics of the battery, the cell type, the module dimension, the power and capacity of the battery, the refrigeration system implemented,

Table 4.1: EV models with their batteries and cooling system.
Soure: Anderman.[79]

Car model			Battery						Refrigeration system		
Car maker	Model	EV type	Chem.	Energy	Cell V	Cell form	Cell Prod.	Batt. Prod.	fluid	air	no
Ford	Focus Electric	BEV	LMO / NMC	23	3,7	Pouch	CPI	LG Chem	X		
Mini	E	BEV	NMC	35	-	Cylinder	-	AC		X	
Mitsubishi	i-Miev	BEV	NMC	15	3,7	Prismatic	LEJ	LEJ		X	
Nissan	Leaf	BEV	NCA	24	3,75	Pouch	AESC	AESC			X
Smart	ED	BEV	NCA	14	3,6	Cylinder	Panasonic	Tesla	X		
Tesla	Roadster	BEV	NCA	53	3,6	Cylinder	Panasonic	Tesla	X		
Renault	Zoe	BEV	NMC	24	3,75	Pouch	LG Chem	LG Chem			
BYD	F3DM	PHEV	LFP	16	-	Prismatic	BYD	BYD			X
Opel	Ampera	PHEV	NMC	15	3,75	Pouch	LG Chem	LG Chem	X		
Toyota	Prius	PHEV	NMC	5,2	3,7	Prismatic	PEVE	PEVE		X	

the battery management algorithms, the communication protocol and the final packaging. A short description and discussion of each one of these aspects is presented in this section.

Cell Chemistry: The concept of "Li-ion battery" defines all kind of batteries having lithium ions as the mechanism for electron transportation between electrodes. However, depending on the performances desired, such as high energy density, high power density, safety or lifespan, the selection of the anodes and cathodes presents subcategories depending on the elements used to create them: Graphite, Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), NMC, Lithium Nickel Cobalt Aluminium Oxide (NCA), LCO, LTO... and each one of them has its own voltage and security limits characteristics as depicted in Fig. 4.2, where the cells with higher voltage are the ones having more thermal instability (red line on the left) or lower lifespan (red arrow on the right caused by lithium platting). Technologies have been changing in the recent years, slowly converging to Graphite/NMC for automotive uses [79], but still there are many alternatives used by different car manufacturers, as it is appreciable in Table 4.1. Battery cells are fabricated adding layers of electrode, electrolyte and separator. The number of layers and its size defines its total capacity.

Functional characteristics: Additionally, knowing that the functional exigencies of the vehicle have a direct effect on the lifetime use [23] and to ensure higher safety standards, car manufacturers added restrictions in the DOD and the Voltage limits differently depending on the objectives of longer life warranties or higher performances. These additional restrictions affect the available capacity of the battery and increase the battery market variability.

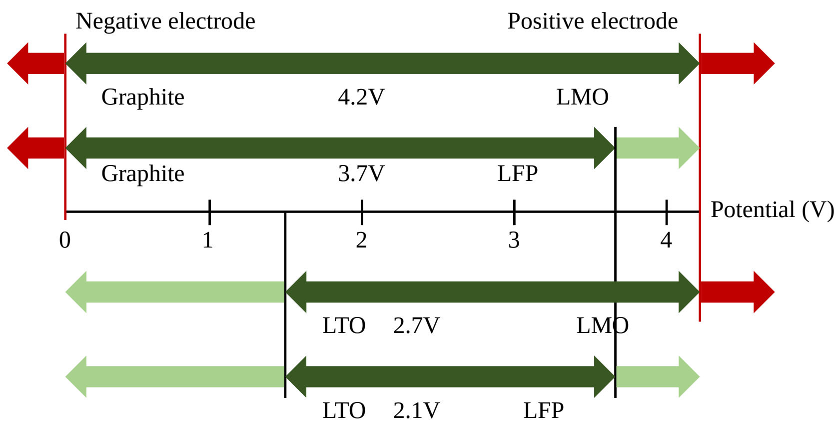


Figure 4.2: Potential (V) between electrodes regarding different lithium cells chemistries. Source: Storage Systems based on Electrochemical Batteries for Grid Support Applications [63]

Cell Type: There are 3 different ways to group the layers forming a cell: Cylindrical, prismatic and pouch. This classification defines the external form of cells, which may have different sizes.

Module dimension: The cells are grouped into modules [80]. Again, we find an enormous heterogeneity in the module design. In fact, the quantity of cells per module differs between car manufacturers or even between models.

Power and capacity: EV, PHEV and Hybrid Electric Vehicle (HEV) batteries are quite different considering power and energy capacity. Typically, EVs have a battery of around 24 kWh, while PHEVs are under 16 kWh and HEV do not get above 5 kWh. Again, the power of a vehicle depends on the performance designed for the model. Nevertheless, 80 kW is a common value. Refrigeration system: Hot temperatures accelerate the battery degradation and aging [81]. Therefore, thermal management is a major concern on EV batteries. Nowadays three options are being used: Forced air, liquid refrigeration or natural refrigeration (none), as it is presented in Table4.1. New alternatives, such as change-phase materials and heat pipe hybridization [82], [83] are expected to appear in the nearby future, although they are not yet implemented. However, these three options have many specialized designs, going from simple cooling plate under the batteries to in-between cells cooling system.

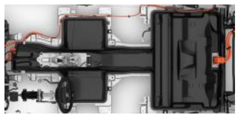
BMS: To control all the aforementioned parameters and ensure the safety and functionality of each battery, there is a particular BMS design using specific electronic equipment. Nowadays these BMS are designed for first use only. This system includes complex algorithms and confidential definitions that should be guarded from foreign watchers. Besides, it also has safety instructions regarding its use on a car, such as key position, door closed, among others to prevent risks that are senseless on 2^{nd} life applications. In fact, due to the absence of these messages in 2^{nd} life applications, the BMS might easily misunderstand signals and make sudden stops or give unexpected errors.

Communication protocol: As said in the previous point, the battery management system is connected to the on-board management system, which controls the rest of the vehicle parameters. This communication is done using a Controller Area Network (CAN) protocol. Although this protocol is used for almost all car manufacturers, each one has defined the messages exchanged between the batteries in a particular way. Hence, the messages from a battery model are not the same as the messages coming from another model. On the other hand, batteries are expected to work alone without any need to identify their messages. That is, two batteries from the same EV model send exactly the same messages; thus, if two or more batteries are grouped, there is no way to identify which messages comes from which battery if nothing is introduced to identify them. One last communications drawback is that, although CAN is well spread in the automotive industry, it is not so for the stationary applications, being Modbus and Ethernet the most commonly used systems.

Packaging and form: Finally, everything is packed together forming a single and safe battery. In addition to all the aspects introduced, there is the available space in the car to deal with, so batteries have to find its place along with all the other components. Therefore, there are T-shaped batteries, others occupying the complete floor of the vehicle, others with two levels, etc. Some of the actual batteries are presented in Table 4.2, as an example of the heterogeneity a 2^{nd} life business has to be able to manage, with the image of different battery forms from different EV models.

In addition to all this design variability, there is another natural factor which produces wider deviations when managing 2^{nd} life battery engineering: The aging of batteries [22]. Batteries are not expected to continue on traction applications after they have lost around the 20% of its capacity [84], [41]. As it happens with all portable devices using batteries, each user exploits them to lower or higher depths, this means that some of the batteries will arrive to the remanufacturing plant with a 70% or less of its initial capacity and others, on the contrary, will come with still a 90% or similar. Indeed, the capacity of a battery is considered to be limited by

Table 4.2: Examples of different EV model's batteries, cell type and modules.

Mitsubishi i-Miev [a]	Nissan Leaf [b]	Opel Ampera [c]	Tesla Model S [d]	VolksWagen e-Golf [e]
				
				

[a] http://www.mitsubishi-cars.co.uk/imiev/technology.aspx. (25-Feb-2014)
[b] http://www.briggsnissan.com/blog/electric-cars-in-manhattan/. (25-Feb-2014)
[c] http://gm-volt.com/2010/03/26/gm-exec-gen-3-voltec-battery-to-have-shortened-lifespan-simpler-shape-and-be-offered-in-smaller-ranges/. (25-Feb-2014)
[d] http://insideevs.com/look-inside-a-tesla-model-s-battery-pac/. (25-Feb-2014)
[e] http://www.fleetsandfuels.com/fuels/evs/2013/11/volkswagen-introduces-the-e-golf/. (25-Feb-2014)

the cell having a lower performance and not all cells age in the same way under similar conditions [85]. Although there is no real consensus in how to define the Battery SOH some tests can be done to estimate it. The problem is that they are very time consuming. According to the VDA initiative "Test specification for Li-ion battery systems", a capacity test takes up to 126 hours and a power pulse test needs 78 hours. These are long time periods for testing that makes the 2nd life characterization complicated and expensive.

4.5 Second life management solutions

This section of the study presents different solutions to confront the aforementioned situations in order to be able to manage 2nd life EV battery businesses. Considering that EV batteries are a pack of modules, cells, electronic and cooling systems, there are two clearly different strategies to follow when dealing with its preparation for reuse: The first one treats a battery as the pack it is, without much more manipulation than a visual and electric check and reuses it directly; the 2nd one is focused on the inner parts of the battery, the process consist in dismantling it into modules to regroup them again forming a new battery product better designed for 2nd life applications [43], [86], [87]. These strategies are called direct reused or battery re-purposing respectively.

The battery re-purposing strategy requires harder work, the use of more components, more time and produces more wastes but it also offers a much more flexible, optimized and fitted functional final unit. However, economically speaking, previous studies presented that the direct reuse strategy can offer a selling price below 100$/kWh, which can be three times lower than following the re-purposing strategy [75]. As the price of new batteries is expected to decrease between 300 to 400 $/kWh in the nearby future [47], the management of 2nd life batteries following the direct reuse strategy is encouraged.

Once the strategy is selected, three alternatives to proceed with its management inside the re-manufacturing plant are presented.

All in one: This option consists in the use of all type of batteries together. A simple battery functional test is done in the re-manufacturing pant to know its SOH and functional capacity. Once characterized, batteries can be prepared for a 2^{nd} life' application or rejected if they are damaged or if their degradation is too noticeable and, thus, batteries are not usable anymore. This alternative might work if the company follows a complete battery strategy with one battery alone, as in autonomous or battery to home (B2H) applications, where the energy storage requirements are similar to the EV battery dimensions [12]. On the contrary, if the preparation of multiple battery energy storage equipment is needed, which is quite provable regarding the power and capacity needs of many 2^{nd} life applications for grid applications, the biggest problems encountered will concern BMS interactions. This study considers a major assumption: all car manufacturers supplied a communications interface or have enough confidence in the company to tell how to extract the information needed to communicate with the battery, which is quite improvable because of confidentiality issues mentioned in section 2. Even considering this assumption, this alternative has the following inconveniences:

- Difficulties to predict SOH and SOC because of the variability of chemistries.
- An almost impossibility to charge and discharge all batteries to the 100%. In fact, batteries always follow the less performing of cells and this is even more visible when mixing chemistries [88]. Hence, if there are cells with, for example, 40 Ah and 15 Ah capacity, when the lower capacity cell is fully discharged the battery will consider that the whole battery is completely discharged even if many other cells have still some capacity left (in this example, 25Ah from the bigger cell won't be used).
- The final product will be well beyond its potential: Packaging all the battery forms and refrigerating systems into a single block would derive in plenty of empty and useless spaces. Therefore, the final result will have low power and energy density.

Even if the solution is not optimal, it might be the first industrial step before the EV takes an important piece of the automotive market. However, it is far from being the best solution.

Selection: This proposal takes all possible batteries into the reusing plant, but instead of mixing them all as in the previous case, there should be a classification according to certain characteristics. With this, most of the previous impediments are eliminated. However, it still depends on the major assumption that all car manufacturers will provide the BMS necessary specifications to the re-manufacturing enterprise.

Once batteries arrive to the re-manufacturing plant the first step could be its separation and classification by some of its characteristics. That is, for example, by battery chemistry, by cell form, by voltage range, by shape, by kWh capacity, by SOH, etc. However, a division by model or car manufacturer directly solves almost all controversies, because an EV model will always have the same battery chemistry, shape, power, energy, cell form, refrigeration system etc.

Then, the only diversity this classification will have is the battery SOH. Consequently, at least a capacity and functional test should be performed afterwards to all batteries, cells and modules (depending of the battery strategy followed). This will provide a determined SOH of the battery and, therefore, the needed information to classify them in families with similar conditions for the best suited 2^{nd} life application.

Again, there are two alternatives to treat and select batteries depending on the industrialization process. Either they use the same production line or they have a specialized line for each type or model. Both options have pros and cons that are briefly discussed in Table 4.3.

EV market sales will help to choose one or another solution or a mixture of them both, such as two specialized lines for the most sold cars and a more flexible one to cover all the other possibilities. However, taking a closer look to the Spanish market numbers, it can be seen that the EV model with more licenses in 2015 made only 388 units from a total of 2.173 sold cars.

Table 4.3: Pros and cons of battery treatment strategies.

Single production line		**Specialized lines**	
Pros	Cons	Pros	Cons
Elevated working rate.	Need of a huge warehouse to store incoming batteries.	Small warehouse, fast entrance to production line.	Some (most) lines will be underused.
Flexible line.	Difficult accessibility and large or exchangeable posts.	Easy to manipulate.	Fixed lines.
Smaller production plant.	In case of problems in the line, production is stopped.	In case of problem in one line, the others might continue.	Need of a big plant to include all production lines.
Production adjusted to needs.	Need of an accurate production program.	Less time per battery	
Multidisciplinary workers.	Higher automation.	Simple and manual lines.	More specialized workers.
Fewer lines.	Higher investments per production line	Cheap production lines.	More lines.

That supposes almost a car per day and, thus, one battery collected per day in 2023 should be expected.

The quantity of batteries arriving to the factory will also determine the degree of automation. Production line posts can be either manually changeable to different battery references or they can have automated multi-reference posts. Meanwhile, specialized lines will have fixed and robust posts, providing higher production rates and confidence but lower capacity of adaptation. Flexibility always takes higher investments but it might also bring better results.

Complete Specialization: With such low battery numbers, and therefore, low revenues [42], some car manufacturers try to help investors to take part into the business, sharing and opening markets, like the joint-venture 4R-energy[1]. These joint-ventures provide the possibility to investigate and get deep into the business knowledge. Additionally, they have confidential agreements, thus, the most optimistic assumption taken in the previous two solutions considering the BMS information exchange is presumably solved in this case. This strategy comes almost with no variety, all it has to handle is the SOH dispersion of the collected batteries.

This solution, evidently, facilitates the plant design, the business plan accuracy (financial support), the implementation of safety issues and the internal management. Moreover, the product standardization facilitates the industrialization, the line automation and simplifies the workers' formation. On the contrary, it also leaves high potential opportunities to other concurrence initiatives. Taking the same example from the Spanish market used in the previous example, and the 388 units from the most sold EV model to the 2.173 of total sold cars, there would still be 1.785 batteries from different brands to collect. In other words, 82% of the whole market will be available for the concurrence.

[1]http://www.4r-energy.com/en/company/ Accessed:2014/02/13

4.6 Conclusions

As all emerging markets, EV manufacturers are still testing and searching the energy storage system that better suits their needs. Therefore, many battery alternatives are being deployed. These many alternatives come with technical and business uncertainties and, consequently, with a great diversity of solutions. This study presented the principal challenges that any attempt to do business with reused batteries will have to face.

All the solutions presented have positive and negative aspects. The options reusing most of the batteries have more technical, formal and management difficulties, while the strategy that is focused on a battery model has more facilities but smaller business market share. The quantity of EV batteries in the collection circuit has to be taken into account to define the business strategy in terms of automation, specialization and selection. As simplicity and standardizing is pursued by most manufacturers, at least a selection of the battery characteristics is encouraged.

Joint-ventures with car manufacturers provide many facilities and reduce investment and production risks considerably, but they also leave business opportunities to concurrence.

Batteries SOH assessment tests should be improved in order to gain competitiveness for reused batteries, classifying batteries into similar conditions will help to ensure the battery pack endurance and will provide robustness and credibility.

The entrance of the EV into the automotive industry will encourage the reuse of batteries, which, at the same time, will provide economic profit that could be used to incentive the EV market and reinforce the virtuous circle. In the end, this will lead to cleaner transportation and to an improved energy system.

Chapter 5

Communications

"It is not that people have become more greedy than in previous generations. What happens is that the ways to express greed have grown enormously".

Frans de Waal, "*Our inner ape*".

5.1 Motivation

Chapter 4 remarked the fact that some difficulties were found in the field of the communications between batteries and the rest of stationary devices. This fact was observed during the development of the Sunbatt project while preparing the communications between the BMS of the batteries and the EMS.

Being a demonstrative project, where many of the battery parameters should be monitored for further analysis and where security and safety was overstated for robustness, the solution that was finally implemented was over-sized.

Nonetheless, the process to choose it required a previous analysis of the possible alternatives passing from the physical layers to the protocols used. As the project was stated from a car manufacturer perspective, the research began with the opportunities available in the field of the EV and V2G was rapidly discarded when the approach was re-oriented in the process when the following though was internalized: if EV batteries are to be incorporated in stationary applications, these batteries should be prepared for stationary applications rather than trying to adapt the stationary systems to the EV batteries' particularities.

Therefore, Chapter 5 presents the results of this communications' analysis at the same time that it goes a little further from the Sunbatt project reality and presents a wider solution, identifying the essential parameters needed by the EMS, proposing an open source protocol and the introduction of a gateway to protect the internal information from the battery.

This chapter is based on the article: *The communications in electric vehicle batteries reuse*, presented to the: IEEE Communications Magazine, which is under the second revision round.

5.2 Introduction

Although it is possible and environmentally profitable to reuse EV batteries, they should compete with other battery technologies (such as common Lead acid batteries, Flow batteries or Nickel based batteries among others) in terms of performances, lifespan and, mostly, price.

In Chapter 6 the different strategies to reuse EV batteries will be described and deeply analyzed; however, a brief summary will be presented to better understand this chapter. It should be mentioned that the reuse strategies go from the battery dismantling combining back the modules to build new ones, to the direct reuse, which has not much manipulation apart from testing. Clearly, it is the direct reuse strategy the one having fewer costs [75]. In addition, this strategy is more accepted by car manufacturers as their product is less manipulated, having fewer risks of failure. Moreover, space and weight are not that relevant in stationary applications as they are for traction purposes, so the extra costs of dismantling and re-building a battery are not expected to be compensated in most of the stationary cases. Thus, this study analyzes the communications needs and possible adaptations of direct reused batteries.

These Li-ion batteries need control and supervision parameters. It is dangerous to overcharge or under-discharge them; The C-rates and working performances inside the safety temperature windows are also limited and, sometimes, voltage range is extra limited in order to ensure longer cycle life.

This control and restriction activities are handled by the BMS or the Battery Management Control (BMC) [89]. In the case of EV batteries, the BMS is placed inside the battery pack, which is completely sealed, and should not be removed or manipulated. The BMS has also specific and precise algorithms containing confidential algorithms, such as the SOH or the SOC algorithms among others and security parameters that car manufacturers do not want to share, neither give the possibility to modify them.

To understand how these BMS are prepared, an analysis of the EV communication system is presented. In the car, EV batteries share and receive the information with the On-Board Charger (OBC), the electric machine, the engine control units, and other car components. This information exchange is done using the Controlled Area Network (CAN) protocol defined especially for vehicles (ISO 11898). The information goes along the CAN bus (a two plait wire) in a sequence of square voltage signals or strings [1].

Having the origin on EVs, the 2^{nd} life could be understood as the step beyond the V2G concept. The V2G interconnection is done following different standards depending on the world region, the objective pursued (which may go from intelligent charging to grid energy services [11] and car manufacturer. As an example, the ISO 15118 using Power line Communication (PLC) system is used in Europe whereas Chademo is functioning in Japan. However, in all these cases, it is the car OBC, not the BMS, the element connected to the Electric Vehicle Supply Equipment (EVSE), which is conneced to the grid elements or utilities with other standards such as IEC 61850, OCPP, OICP, etc [90]. Thus, as the 2^{nd} life of EV batteries will use no OBC, neither an EVSE to manage the storage system, no advantage can be taken from V2G solutions and another approach should be studied based mainly on the battery.

As it has been shown in Chapter 4, EV batteries are all but standardized, each car manufacturer uses his own technology and package, the battery form is different for each car and model and so it is the refrigeration system [86]. They are built by the addition in series of various cells forming modules of certain voltage and capacity and then grouping several modules into battery packs (Fig. 5.1). The number of cells forming a battery depends on the type of cells, the power

[1] http://www.docstoc.com/docs/97829831/Controller-Area-Network. (06-Oct-2014)

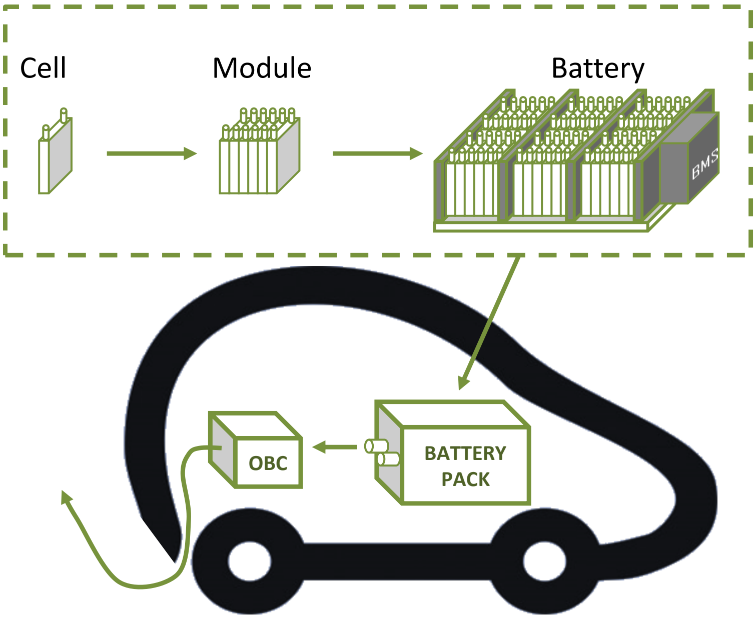


Figure 5.1: Battery composition from cell to battery pack.

and the capacity of the battery that each manufacturer defines for each car model. E.g. the Renault Twitzy has 42 cells, the e-golf has 264 cells or the Tesla Model S has 7.104 cells.

Each of these cells has a cell-controller observing the voltage evolution, information that is sent to the BMS. Additionally, each module has also a voltage evaluation and has, at least, one temperature sensor. Again, the BMS gathers this information. The whole package has a refrigeration system, controlling the temperature the coolant (air or water), the fan revolutions, the pump regulation... Depending on the car manufacturer, vehicles have other elements controlling the battery: current meters, power calculations, SOH algorithms and prognosis, fuses, isolation checks, and many other security devices ensuring no danger while driving an EV.

After all, each EV battery has, easily, more than 500 signals and messages going from and to the battery and each car manufacturers codifies them differently.

Based on the experience learned from the Sunbatt project described in Chapter 3, this study explores two alternatives to solve the particular communication's complexity of EV batteries' reuse and presents the minimum number of parameters that must be exchanged.

5.3 Approach

In the first place, a description of the possible 2^{nd} life applications and the elements involved will be presented. Then, it continues with the physical communication system and the possible protocols to be used in these fields. Finally, this section tries to understand how these communications protocols and systems match with the reused battery configuration.

5.3.1 Stationary applications batteries' environment

Batteries may participate in all the stages of the energy grid, from the energy generation to the distributed energy resources and into home applications providing different services, benefits and revenues [16]. The renewable energy generation is variable and depends on weather conditions and yearly seasons; energy storage systems offer the opportunity to eliminate this disadvantage, ensuring the programmed generation and enhancing the implementation of clean energy systems.

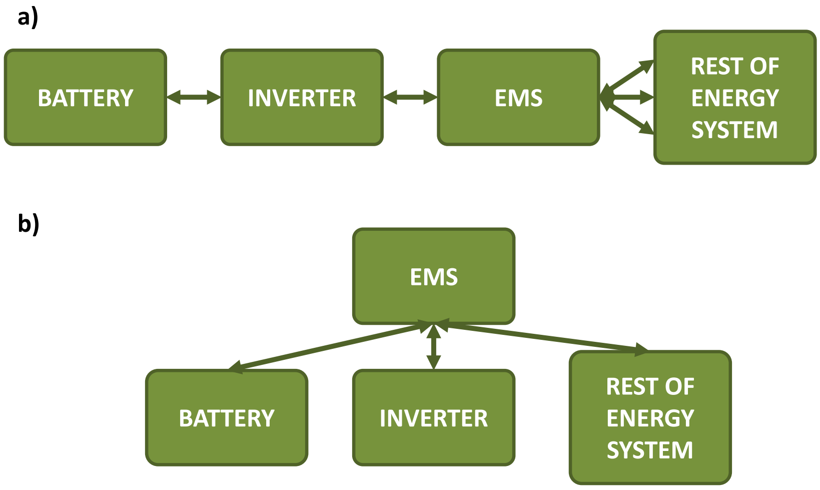


Figure 5.2: Communications diagrams of the battery and the rest of elements in a grid.

Batteries can be used to balance the energy production and demand, being able to use the energy plants at their optimal level and reduce emissions or shut down polluting power plants. Additionally, they facilitate the decentralized generation serving as energy buffers and helping the energy area regulation. At a distribution scale, they can be used to ensure quality and enlarge the installations lifetime. Finally at home/building level, they offer the possibility to reduce the electricity bill by buying the energy at lower fares and using it when the energy is more expensive or by reducing the power factor tariff using the battery for peak shaving. Additionally they facilitate the introduction of autonomous and island installations. This wide range of opportunities means that, in one way or another, batteries will interact with all the elements composing a smart grid: from a wind turbine to a dish-washing machine.

Nevertheless, this does not imply that batteries should communicate with all the elements and grid participants at the same time. A wiser approach indicates that batteries are used as a support or slave element in the system that takes no energy management decisions, which are held by the EMS. Thus, batteries just need to communicate their status and conditions to one or two elements at most, as presented in Fig. 5.2.

These are:

- The *inverter* that comes just after the battery so the energy will be transformed from DC to AC and vice-versa. It is the solution stablished in the Sunbatt project, where the 4 PHEV batteries are connected to the inverters.

- The EMS that controls the loads, limits and generations of the grid.

5.3.2 Physical communications

There are mainly three ways to communicate between electronic elements: The Shared Line systems, using the normal power or telephone lines adding signals at different wide frequencies; The specific lines, as IEEE1394, Ethernet, USB, etc.; and the wireless systems, such as Bluetooth, ZigBee, Z-wave, Wifi, Wimax, GSm among others. This section will propose the most suitable option considering the elements with whom the reused EV battery has to communicate.

In the first case analyzed (Fig. 5.2a), the battery is connected to the inverter and, this one, to the EMS, who takes the decisions. That is, the inverter works, in the communications field, as a transmitter from battery to EMS. Normally, the inverters use RJ-45/Ethernet/TCP-IP, RS-232 or two intertwined wires for CAN. Currently, as mentioned in the introduction, EV batteries exchange information via a CANbus using a specific codification of the CAN protocol based on the ISO 11898.

Hence, the most effective, economic and practical system to use for the first case (Fig. 5.2a) is the communication via CAN, as both elements have it already implemented. The difficulties might come from the communication protocol and codification each one uses, which is going to be discussed in subsection 5.4.3.

For the second case (Fig. 5.2b), the battery is directly connected to the EMS. There are many type of EMS. The EMS can be implemented in many electronic supports, the most used in automation are SCADA or other computer based systems, whereas HEMS is more specific for home applications. None of them are used to communicate via CAN. None of them use CANbus, they usually have TCP/IP or wireless connections.

In this second case, there is clearly a mismatch to be solved as the physical systems used are different. This can be solved by the use of bridge communication devices available in the market as a primary or temporary solution. From an installer point of view, the battery reuse would be enhanced if EV batteries were prepared for the second life with an Ethernet or TCP/IP input/output connector. Howbeit, it is hard to foresee this option, as that would signify an extra cost for car manufacturers during the EV life cycle that maybe won't be used afterwards. in addition, car manufacturers might be able to sell these bridges as an extra service or a complement at the end of vehicles life.

Thus, the proposed system is similar to the configuration described in the work from Zhu et al. [91], where the management system uses Ethernet and the storage and load systems use CANbus for the fast and practical signals.

5.3.3 Protocols

There are multiple choices in the market of conventional batteries and BMS to select the ones that best suits each application's needs. However, in the introduction it was stated that reused batteries would be delivered together with its BMS integrated, having no possibility to choose.

Although the BMS and most inverters use the CAN protocol, its configuration and signal codification is different. Therefore, a CAN matrix is absolutely necessary to decode the messages sent to and through the battery. However, car manufacturers are not willing to provide this CAN matrix, because that would mean direct access to the internal messages, the battery confidential information, and an undesired risk for parameters manipulation.

A possible solution for this incompatibility is the addition of a gateway that would allow the exchange of some of the messages, but will block the others. In order to provide a higher security level, the information will be translated into different arrays, so the final receiver couldn't know the original CAN codification and protocol from the vehicle.

This Gateway should be understood not only as a firewall and translator, but as an active element too. As mentioned in the introduction, the reused battery expects some messages from the OBC in the car, as in stationary application there is no OBC nor a car, this gateway should provide these expected security messages to the BMS, such as "key position". For example, an industrial PC was used for this purpose in the Sunbatt project [92].

In the first case of study (Fig. 5.2a), In order to have a public and open source protocol and codification, the selected communication protocol used by the gateway is proposed to be CANopen. This protocol was designed for automation applications and follows the CiA301 (CAN in automation) which is based, among others, on the same ISO 11898 used in the automotive industry. The bridges to pass from CAN to CANopen are easy to build, as CANopen is a higher level protocol, meaning that it adds terms in the data string identifying the application, the element sending the message and other significant characteristics and it contains in the end, the aspects like datalink and physical strings from the CAN protocol [93].

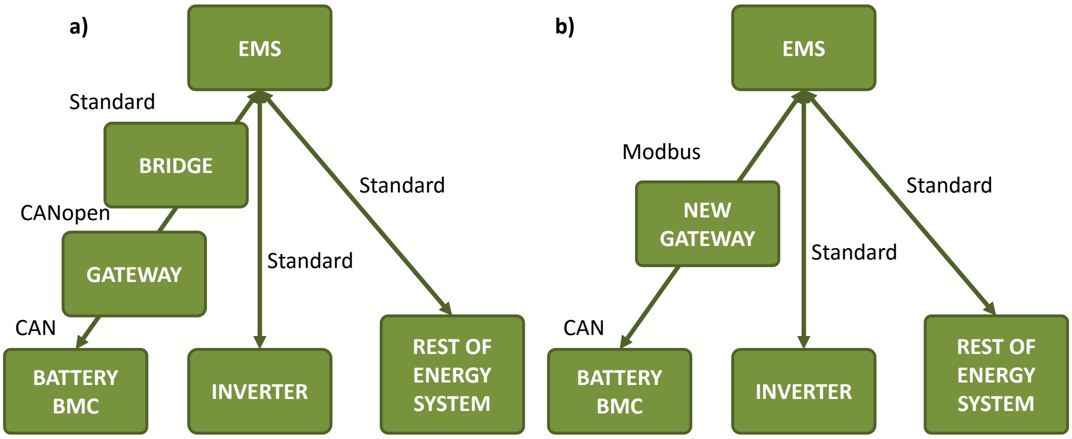


Figure 5.3: Schema of the elements and the protocol used connected to the EMS.

In the second case (Fig. 5.2b), where the BMC is connected to the EMS, two options may be chosen: Either use a commercial bridge from CANopen to the protocol used in each case by the EMS (according to the physical system that best suits the specific installation (PLC, Wireless, Ethernet...)) or that the gateway provided by the car manufacturer, instead of giving the signal in CANopen, it provides it in Modbus or any other Ethernet compatible protocol (Fig. 5.3). This second option is less probable as there is a huge diversity of EMS programming. In some cases the EMS manufacturer is also providing solar panels, inverters and other smart grid elements using its own protocol to ensure no communication failure. Consequently, some bridges would be needed anyway.

As the communications between the inverter or EMS and the other devices in smart grids are already implemented in many applications, the protocol and physical transmission system presented in Fig.5.3 are written as Standard.

After this analysis, it was found that, in the end, the solution that would fit in all cases is to use a gateway using CANopen protocol and, if needed, acquire a commercial bridge with the protocol and physical layer expected by the receiver or EMS.

5.4 Exchanged information with the smart grid

Taking the example of the Sunbatt project, this section analyzes the messages that should be selected and exchanged from the battery to the EMS or inverter. As a reminder, the Sunbatt project conceives the energy storage as a portable device that may be connected anywhere. That is the reason why the batteries, the cooling and refrigeration systems and the power electronic equipment are placed inside a maritime container as schematically presented in Fig.3.11 on Chapter 3. In the particular case of its installation in the SEAT facilities, the container is connected to 4 EV chargers, solar panels and the local grid. The EMS is the element taking the energy management decision while the SCADA is the system that activates the different electronic elements. In future prototypes, it is expected that the EMS will be integrated in the SCADA. In the meanwhile, the SCADA concentrates and sends the information of all the elements to the EMS, working as a bridge. As mentioned in the protocols subsection, the element described as PC in Fig.3.11 should be understood as the gateway described all along the study. It connects the batteries' BMS with the inverters that are connected to the SCADA and EMS in the end. Additionally, although it could be executed by the EMS or SCADA, this PC is also connected to the cooling system of the container and refrigeration system of the batteries, which was adapted for space optimization.

The EMS is programmed following two strategies: to maximize economic profit and to reduce the CO_2 emissions with 90kW power limitation. To do so, the EMS receives information from outside the container: Grid pricing, in order to buy energy at lower fares and sell it (if permitted by local regulations) when it is expensive; Grid electricity generation's Mix to control the emissions; Meteorological forecast, so it can predict the Solar panels production and grid necessities in case of power supply emergencies and grid load predictions.

In the Sunbatt project, the batteries will absorb the extra energy produced by the solar panels if there is not enough consumption from the charging EVs and offer it back when there are sudden power interruptions, at night or to provide the necessary power at peak power demands when all chargers are simultaneously active. At the same time, the batteries are able to store energy when the cost of electricity, or the electricity Mix emission factor, is low, and then use it when the fares are higher or the energy generation is polluting.

In order to manage the energy properly, apart from load and demand prognosis, the EMS needs some information of the state of the battery. In this section a proposal of the minimum data needed for a correct energy management using 2^{nd} life batteries will be reasoned. See the summary in Table 5.1.

The battery power depends on its voltage (V) and current (I). Although these parameters can be evaluated from outside the battery, for security reasons it is useful to validate that the voltage and intensity through the battery and inverter coincide. In order to know the maximum power the battery can offer, the EMS should know the maximal current (I_{max}) the battery can deliver at every instant.

This I_{max} depends on the SOC and temperature (T) of the battery. Its limitations are controlled by the BMS inside the battery. Additionally, the EMS should be able to provide power along time and not incur into sudden and unexpected current limitations. Consequently, it should know the maximal sustained current ($I_{maxcont}$). Similarly to current, voltage is also limited. The voltage in a battery varies depending on SOC, I, T and other chemical mechanisms [94], being its limits controlled by the BMS. Thus, the EMS might need this information for maximal and minimal Power (P_{max} and P_{min}) calculations.

As it has just been specified, SOC and T do have an impact on the battery performance. Temperature could be used, for example, to activate the refrigeration system that warrants the battery durability. Thus, it is necessary to receive this signal and the temperature working limits (T_{max}, T_{min}).

SOC provides information of the quantity of energy still available in the battery. Conceptually, it is defined as the ratio of the available energy or capacity (Cap) divided by the total capacity (Cap_T) of the battery when fully charged (eq.5.1). The capacity is measured in Ah.

$$SOC = \frac{Cap}{Cap_T} \tag{5.1}$$

But, with time and use, the battery becomes less and less performing. Its initial capacity is no longer available, that is why the second life is considered. This phenomenon is called capacity loss [26] and it is evaluated by the SOH which is defined by the division of the actual total capacity by the initial total capacity (Cap_i) (eq.5.2).

$$SOH = \frac{Cap_T}{Cap_i} \tag{5.2}$$

Then, combining equations eq.5.1 and eq.5.2 it can be seen that only three of these parameters are necessary. As all BMS control the SOC of a battery and have the information of the Cap_i, these two will be taken into consideration. The SOH is an estimated parameter with many different ways to calculate it [95], [96], [88]. In fact, each car manufacturer uses its own designed algorithms for these calculations, which are part of the confidential information that should not be exposed elsewhere.

The value from SOH will be also considered as necessary information available by the EMS. The designed storage system might have one or multiple batteries connected to the EMS [14]. Having more than one battery connected at the same time is a situation not previewed during the car design, as each vehicle has its own battery and should interact with no other. For this reason, in most cases batteries do not have an identifier. This identification number should be added by the gateway (Id). The final signal to be exchanged by these elements is the working mode of the battery. In EV, this mode switches between Off, Stand-by, Charging, Driving and Balancing. The normal status of a battery in use in a stationary application will be "*drive*", because it is the only status that allows both discharging and charging (energy recovery braking) situations. Anyhow, EV batteries consist of many cells connected in series and parallel, and the cells perform softly different. Hence, once in a while, it is needed to do some cell battery balancing. The best way to balance the cells in a battery is under no solicitation, i.e. the battery does it when there is no energy requirement, when the voltage is stabilized and without any need of external connection. It is the BMS defined by the car manufacturer who's running the cell balance.

Summarizing, all the needed parameters and their use are presented in Table 5.1.

Table 5.1: Signals exchange between the gateway and the EMS.

Parameter (unit)	Name	Use	Type	From
Voltage (V)	V	For instant power calculations	Variable	Battery
Maximum Voltage (V)	V_{max}	Future charge power calculations	Constant	Battery
Minimum Voltage (V)	V_{min}	Future discharge power calculations	Constant	Battery
Current (A)	I	For security issues	Variable	Battery
Max. Current (A)	I_{max}	For power and energy calculations	Variable	Battery
Continuous Max. Current (A)	$I_{maxcont}$	For power and energy calculations	Variable	Battery
Temperature (K)	T	For battery working conditions optimization	Variable	Battery
Maximum Temperature (K)	T_{max}	For security issues	Constant	Battery
Minimum Temperature (K)	T_{min}	For security issues	Constant	Battery
Initial Capacity (Ah)	Cap_i	For energy calculations.	Constant	Battery
State of Charge (%)	SOC	For energy calculations	Variable	Battery
State of Health (%)	SOH	For energy calculations and maintenance planning	Variable	Battery
Battery Identifier	Id	To manage correctly the energy distribution	Constant	Gateway
Battery working mode	Mode	To allow balancing and maintenance	Variable	Battery

EV batteries are built by the addition in series of various cells forming modules of certain voltage and capacity and then grouping several modules into battery packs (Fig.5.1). The number of cells forming a battery depends on the type of cells, the power and the capacity of the battery that each manufacturer defines for the car.

Each of these cells has a cell controller observing the voltage evolution. This information is received by the BMS. Additionally, each module has also a voltage evaluation and has at least one temperature sensor. This information is also taken by the BMS. And the whole package has a refrigeration system, controlling the temperature of the cooling system (air and water), the fan revolutions, the pump regulation... Depending on the car manufacturer, the vehicles have other elements controlling the battery: current meters, power calculations, SOH algorithms and prognosis, fuses, isolation checks, and many other security devices ensuring no danger driving an EV.

After all, each EV battery has, easily, more than 500 signals and messages going from and to the battery but most of them are useless for the EMS on stationary application. Indeed just the aforementioned 14 messages (Table 5.1) are needed for a proper energy management.

5.5 Conclusions

After the analysis it has been concluded that current EV batteries on stationary applications will be connected, as any other new battery, to the EMS or to the inverter that transforms the DC current of the battery to AC for the smart grid.

In both cases the battery connection will be done by a two braid wire to a gateway. This gateway should use also a two braid wire connected to the inverter using the CANopen protocol. If it is connected to the EMS, the gateway output should be one of the accepted by EMS or another commercial bridge should be added doing the change from CANopen to the needed physical layer and protocol from the EMS.

It is proposed that the gateway will use a CAN matrix changing the Battery codification to ensure confidential protection and it will also provide the responses expected by the battery to simulate the car conditions.

From all the messages (more than 500) exchanged by the battery and the rest of the EV, only 14 messages are needed by the EMS. Additionally, only 8 of these values are variable.

If this proposal is taken into consideration by car and battery manufacturers, it would facilitate the implementation of storage devices into smart and micro grids. The signals proposed to be exchanged with the EMS have no confidentiality impediments and the CAN matrix installed in the gateway could be sold by the same car manufacturers, ensuring no intromission and expanding the after-sales business.

Finally, knowing that car manufacturers are the principal actor for the 2^{nd} life of EV batteries to success, we should expect that future EV battery designs will include either a 2^{nd} life mode function or the aforementioned gateway included in the packaging.

Chapter 6

Re-purposing cost analysis

"Je ne puis m'empêcher de craindre que les hommes n'arrivent à ce point de regarder toute théorie nouvelle comme un péril, toute innovation comme un trouble fâcheux, tout progrès social comme un premier pas vers une révolution, et qu'ils refusent entièrement de se mouvoir de peur qu'on ne les entraîne."

Alexis de Tocqueville, "*De la démocratie en Amérique*".

6.1 Motivation

The main purpose of investigating in the 2^{nd} life of EV batteries, from the perspective of car manufacturers, is the profitable business that may lay behind. However, before delving into the possible revenues, a cost analysis should be performed.

Additionally, it has been mentioned that the price of Li-ion batteries is far too expensive to enter into the stationary applications market.

Consequently, a re-purposing cost analysis of EV batteries to prepare them for the second life should be realized before any business case is seriously addressed.

The results of this cost analysis is presented in this Chapter 6 for the two re-manufacturing strategies of EV and PHEV batteries: direct reuse and module re-manufacturing strategy. This cost analysis is carried out under two different scenarios: first stages of the battery reuse (when not many batteries are available) and a full capacity re-manufacturing plant.

The cost analysis reveals that, again, the SOH assessment is responsible of a huge part of the battery cost re-purposing, and that the reuse of EV batteries is more cost-effective than dealing with PHEV batteries.

This economic results will be further used to calculate the amortization cost of batteries in Chapter 8, where the RUL of these batteries in different applications is studied.

This chapter is based on the article entitled *A cost analysis of electric vehicle batteries second life businesses* that was presented in the XVIII International Congress on Project Management and Engineering congress (CIDIP). This article was selected to be part of the Springer's conference proceeding book: *Project Management and Engineering 2016* in chapter 10. Book ISBN: 978-3-319-26457-8; Book ID: 340977 1 En.

6.2 Introduction

The Electric car is presented as a possible future solution to reduce CO_2 emissions from the transportation sector. Government's efforts on the transport sector CO_2 emissions are a key factor to accelerate or retain the EV entrance into the automotive market. Anyhow, even in the less optimistic case, thousands of EVs are expected to be sold during the following years [69]. In fact, in the Spanish market (Fig.6.1), the number of EVs registered in 2013 doubled the quantity from 2012, surpassing the 1.000 cars for the first time. This tendency has been sustained until 2015, when 2.173 EV where sold. Anyhow, it should be noticed that two car manufacturers (Nissan, Renault) cover more than the 80% of the EV market.

The EVs are actually powered by batteries, most of them based on lithium technologies [97]. As most of things in life, batteries get degraded with its use [22]. For traction use it is considered that they are not appropriate anymore when they have lost between 20 and 30% of their capacity or power. At this point they should be removed from the car and, normally, collected for recycling.

European directives try to force batteries and accumulators wastes collection. They do it putting some pressure on battery manufacturers, charging them the costs of recollection (Directive 2006/66/EC) and setting collection targets of at least a 45% of the sold batteries by 2016. Although intended, this does not usually happens for the small batteries on the market and, in fact, this target seems hard to achieve because of the inefficient battery and waste electrical and electronic equipment collection network and because, in many cases, batteries are fully integrated in some appliances [98].

Anyhow, EV batteries don't follow the same directive, and the responsibility to collect and recycling the batteries falls on car manufacturers. For them, up to 85% of the car weight should be recycled and another 10% can be energetically recovered. Therefore, it is important not to lose any after its life in a vehicle, even if recycling batteries costs, nowadays, hundreds of Euros[1].

[1]http://www.lithorec.de/ Accessed: 13/03/2014

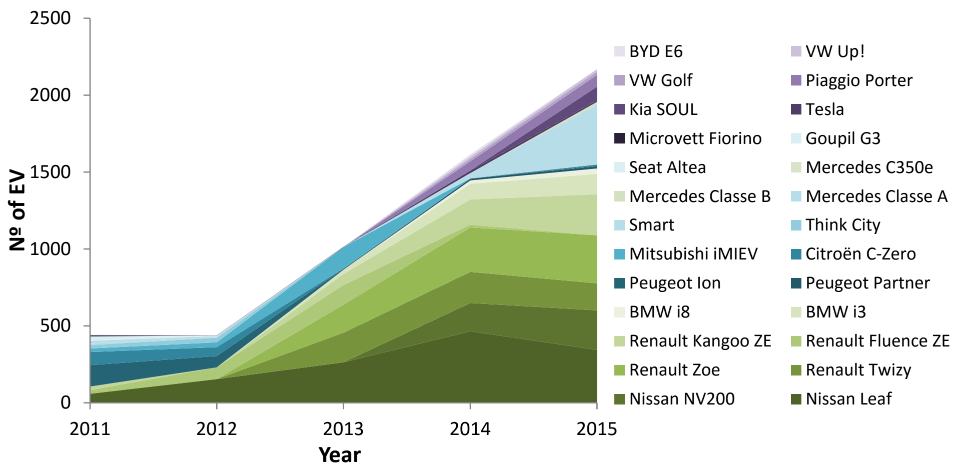


Figure 6.1: Evolution of EVs registered in the last years in Spain. Source: ANIACAM

There's one alternative to recycling though. Even if the EV batteries are not performing as well as brand new ones, they are still in quite good conditions compared to the average energy storage systems used in stationary applications. Therefore, some economic and useful value might still be extracted from them with second uses before recycling.

From this point of view, second life's added value might help to improve deposition and control because the owner of the battery has something to gain. This is, indeed, not the only positive result: Second life might also lower the EV prices and make them slightly more attractive against the ICEV, it won't have an extreme impact, but everything is welcome from the cost-reduction side [99]. Still into economics, re-using batteries might evolve into lower battery prices for stationary grid applications and, hence, the implementation of micro-grids and decentralized energy production, as well as the definitive integration of smart-grids and their supposed benefits [73], [100]. And finally, a direct environment impact reduction is driven from the use of second life's EV batteries [42]. If reuse finally exists, fewer new batteries should be manufactured.

All these encouraging aspects brought the idea of re-using them for Battery to Grid (B2G) applications. In fact, first economical approaches have been presented, although they used inaccurate life-length assumptions, [42], [101].

Even though interesting, second life reuse is not a plug-and-play story. Batteries should be collected, revised, tested and arranged if necessary. Then, regarding its SOH, they should be classified and stored until the second-life installation is prepared. All these works on batteries should be translated into costs. The subtraction of these costs to the 2^{nd} life application's incomes and profit will resolve the "willing to pay" value for these used batteries. If these values are high, all the positive aspects will go on, but if it is too low or negative, there will be not much hope. This work will present the estimated costs for rehabilitation of EV used batteries. This is the first step needed to continue with the second-life's debate.

6.3 Methodology

This section begins with a brief analysis of the battery circuits during its first use in vehicles and their collection for reuse or recycle. The recollection costs will be estimated from received offers by battery management integrated systems.

There are three main types of electric cars: HEV, PHEV and full electric EV. Second life has sense with big battery packs; therefore, the study will only consider batteries from PHEV and EV.

For these batteries, there are two main strategies to face rehabilitation. The first one is meant to reuse the batteries without much intervention. That is, trying to reuse the batteries

Table 6.1: Comparison of the two basic rehabilitation strategies

Direct reuse		Module reconfiguration	
Pros	Cons	Pros	Cons
Faster battery check	Rigid final product not suitable for all 2^{nd} life applications	Optimized final product for specific 2^{nd} life application	Much more preparation time
Easier rehabilitation process	Big battery manipulation	Manipulation of manageable modules	Need to build the new configuration.
Reuse of all components	Need of additional interfaces for communication.	Adapted BMS and refrigeration system	Design and programming of new components
Cheaper	Stackable at battery level	Stackable at module level	More expensive

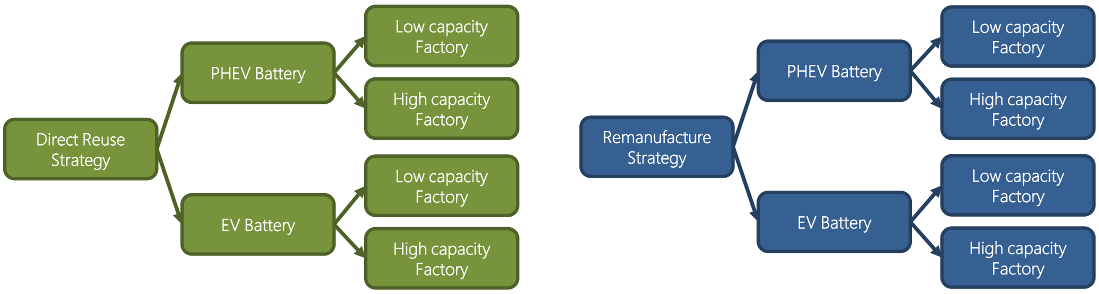


Figure 6.2: Summary of the studied alternatives.

in the same configuration as it is used in the car: same shape, same refrigeration systems, same covers... as if it was a black box [87]. The second one opts to dismount the battery in modules or cells and re-arrange them in a better configuration for its second use [43]. Some of their main characteristics are presented in Table.6.1. In this work, both strategies will be analyzed.

A cost analysis is presented based on recollection costs, functional and health tests, rehabilitation plant investments amortization and production time costs. Knowing that nowadays, and until at least ten years from now, the number of batteries available will still be low, two approaches are studied: one for a rehabilitation plant using 176 batteries per year, where workers are far from being saturated and they have many waiting or spare time; and another one considering enough batteries to support a factory with an optimized productivity. That is:

- For the direct reuse strategy: 6 test benches working simultaneously providing a total of 1056 batteries per year for both PHEV and EV with one worker per turn.
- For the module reconfiguration: two workers per turn to run 3 test benches for 528 PHEV repurposed batteries annually and 2 test benches to work on 352 EV batteries.

For this work, the rehabilitation plant will be located near one of the most important car manufacture centers in Spain, close to the city of Barcelona. Although theoretically this rehabilitation plant could take batteries from all EV manufacturers, we planned just working with only one battery type. It has to be taken into account that there is a huge diversity in batteries and that there is many confidential information contained in a battery pack. In addition the responsibility of these batteries along its lifetime will fall under the car manufacturers. Therefore, car manufacturers will surely work hand-to-hand with only one company, like it is the case of 4R-energy.

All the analyzed alternatives are summarized in fig.6.2.

6.4 Discussion

Cars are manufactured mostly in one production plant in Europe and then, spread all around the territory or even abroad and overseas to car dealerships. Batteries should follow the same path, but the opposite way (fig.6.3). In the EU and in Spain in particular, after the end of useful life, cars should be disposed at the Authorized Treatment Centers (CAT)s for dismantling. They can arrive there in different ways:

- The owner leaves the car to the dealership where he will buy a new one. Then, the car dealers should send the car to the CAT for dismantling.
- The owner brings the car directly to the CAT.
- There are municipal services that pick-up abandoned cars.

Table 6.2: Car dealerships distribution in five cities for different car manufacturers

Barcelona	Sevilla	Bilbao	Madrid	Santiago de C.	Car Manufacturer
39	10	10	43	13	SEAT
21	9	10	49	2	RENAULT
18	4	8	26	2	CITROËN
14	1	5	15	1	MAZDA

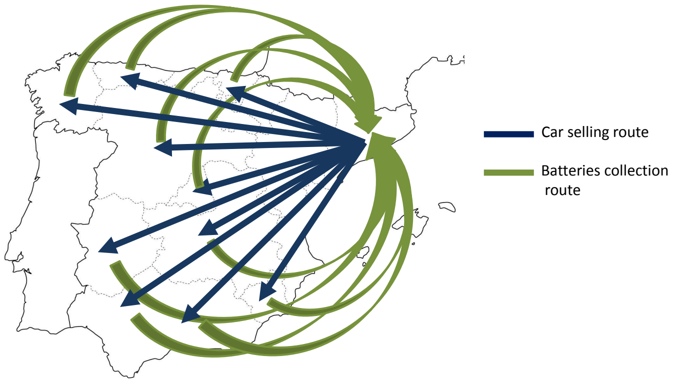


Figure 6.3: Car selling and batteries collection opposed paths.

The government incentives in renewing the automobilist park and the easiness given by car dealers, favor the first option[2]. In any case, all these related costs are not taken into account in the analysis because they do not differ from the actual situation of ICE cars, so there should be no extra cost. Anyhow it serves to understand the starting locations for battery collection. From Table6.2 it can be observed that different car brands follow similar selling strategies, concentrating their efforts in the same cities [3], [4], [5], [6].

There are more than 1200 CATs spread all around Spain, most of them are located near the places where more cars are sold [102].

Once there, the vehicles are dismantled and their battery removed. These costs will still not be taken into account in the calculations because it does not differ from the actual situation. This is the last common path from IC vehicles and therefore, the last nonspecific cost attribution.

It will be considered that no battery statement will be done at the Authorized Treatment Centers CAT where cars are deployed at the end of their lives. According to legislation, damaged batteries are considered hazardous merchandises [103], so their transportation should be done in special conditions: They should be placed inside two containers and at least one of them sealed and fire-resistant, increasing the transportation costs. Hence, although batteries conditions will not be determined, only batteries from crashed cars will be considered as damaged batteries. In fact, these batteries, for safety reasons, won't be used for rehabilitation and their managements costs will be added to the final value. According to the Spanish Government [104] and from interviews done on local CATs, the number of crashed cars arriving at their installations is lower than 10%.

[2]http://www.minetur.gob.es/energia/es-es/servicios/vehiculoeficiente/paginas/programa-vehiculo-eficiente.aspx Accessed: 2014/01/31

[3]http://www.seat.es/content/es/brand/es/contact/red-seat.html Accessed: 2014/01/31

[4]https://www.mazda.es/localiza-tu-concesionario/ Accessed: 2014/01/31

[5]http://www.citroen.es/contacto/red-oficial/ Accessed: 2014/01/31

[6]http://www.renault.es/concesionarios/ Accessed: 2014/01/31

Then, batteries will be transported to the rehabilitation plant (Fig.6.3). As there are more treatment centers than registered EVs in Spain, it is highly improbable that one particular CAT receives more than one battery per month. Hence, it will be considered that each battery will be collected individually from the CATs when they eventually receive an EV and take the battery off.

Once batteries are at the factory, they should first be checked at determined conditions using climate chambers and precise electronic equipment. Nowadays, these tests are neither fast nor simple [62], [58]. In fact, the VDA initiative, formed by the vehicle manufactures, has defined in the "Test specification for li-ion battery systems" a capacity and power pulse tests that, if strictly followed (Table 6.3), take about 126,25 and 78,6 hours respectively. These timings are too long for any business to run, therefore we will consider that a time improved test will be executed lasting no more than 24h (by implementing test improvements such as the novel proposal developed in Chapter 7).

Depending on their performance results, batteries will be classified according to the second life applications needs. Then, special arrangements and maintenance tasks will be done, such as the implementation of communications interfaces to adapt the BMS strategies to the needs of second use applications or change degraded materials. Finally, they will be checked again in order to validate the complete functionality. This final check won't be as demanding as the first one because it is not intended to search the battery SOH, it just checks if it will be able to execute the requested services. It should be noted that batteries coming from crashed cars will be immediately sent to recycling plants.

For the module reconfiguration strategy, batteries will be dismounted before the first functional check and then each module will be verified independently following the same procedures. Once checked and selected, the modules will be regrouped in categories to build a new battery

Table 6.3: Capacity and Power pulse tests description from VDA-Initiative (2007/03/05).

Capacity test	Power test
Standard Cycle	Acclimatization at 40ºC
Acclimatization at -25ºC	Standard Cycle
Discharge 1C	Acclimatization at 40ºC
Charge at cell nominal (C/3 normally)	Discharge 1C until 80% SOC
Wait 30 minutes (for temp. stabilization)	Acclimatization
Repeat 3 times Charge/discharge cycle	Pulse:
	Discharge at Imax for 18s;
	Relaxation for 40s;
	Charge at 0.75*Imax for 10s
	Relaxation for 40s;
Acclimatization to RT	Discharge until next SOC step
Discharge 10C	Repeat for SOC 65%, 50%, 35%, 20%
Charge at cell nominal (C/3 normally)	Standard Charge 1C
Wait 30 minutes (for temp. stabilization)	Acclimatization at RT ºC
Repeat 3 times Charge/discharge cycle	Standard Cycle
Acclimatization to 40ºC	Repeat Pulse test for all SOC steps
Discharge 20C	Acclimatization at 0ºC
Charge at cell nominal (C/3 normally)	Standard Cycle
Wait 30 minutes (for temp. stabilization)	Repeat Pulse test for all SOC steps
Repeat 3 times Charge/discharge cycle	Acclimatization at -25ºC
Acclimatization to RT	Standard Cycle
Standard Charge	Repeat Pulse test for all SOC steps

pack completely different from the original car battery, it can be smaller or even bigger. The main difference is that in this case, the refrigeration systems and the BMS will be completely new, while in the previous case they will also be reused.

Then, the rehabilitated batteries will be stored in a special warehouse, with all the safety systems required, waiting for its shipment to their new installation.

6.5 Results

The most valuable element in lithium batteries to recycle is Cobalt. Therefore, recycling plants just pay to receive the ones containing more than a 5% of its weight. As EV batteries have much less than this percentage of Cobalt, it is the manufacturer who has to pay for them to get recycled. Taking an average of different offers received, it has been calculated that the collection of a PHEV battery should cost around 170€ while EV ones will rise up to 316€. Their packaging is considered to cost 20 and 38€ respectively.

Calculations follow with the re-manufacture plant costs, which will take investments, consumables and personal costs.

In order to have an approximation to the plant dimensions and costs it is important to know the production time and processes. In general, EV batteries are twice as big as PHEV ones, then, the dismantling and module reconfiguration strategy using EV batteries needs more time than using PHEV ones. This does not occurs when running the Direct reuse strategy, as the battery is treated as a pack. Table 6.4 shows the comparison of the production time associated to each of the strategies followed and the battery size to prepare. It can be appreciated that the difference between both strategies is 10,5 and 20.9 hours for PHEV and EV batteries respectively. This is equivalent to say that the reconfiguration strategy needs 3,5 and 6 times more manipulation time than using the direct reuse strategy.

As presumed, bottleneck is found in the battery test and test preparation operations. The duplicity of testing benches or lines would help to substantially reduce waiting times (Fig.6.4). For the direct reuse strategy, starting with one worker doing both initial and last operations (Physical inspection and maintenance), up to 6 batteries could be tested simultaneously, having one battery ready every 4.7 hours (n=6).

Table 6.4: Time distribution of direct reuse and module reconfiguration strategies

Direct Reuse		Module reconfiguration		
Operation	PHEV & EV time (h)	Operation	PHEV time (h)	EV time (h)
Physical inspection	0,5	Physical inspection	0,5	0,5
		Battery dismounting in modules	5	9
Test preparations	1	Test preparations	2	3,6
Battery test	24	Battery test	24	24
Disconnection and battery classification	0,5	Disconnection and modules classification	1	1,8
Interface mounting and maintenance	1	Battery rehabilitation	5	9
Functional battery tests	0,5	Functional Battery tests	0,5	0,5
Storage	0,25	Storage	0,25	0,25
Shipping	0,5	Shipping	0,5	0,5
TOTAL	28,25	TOTAL	38,75	49,15

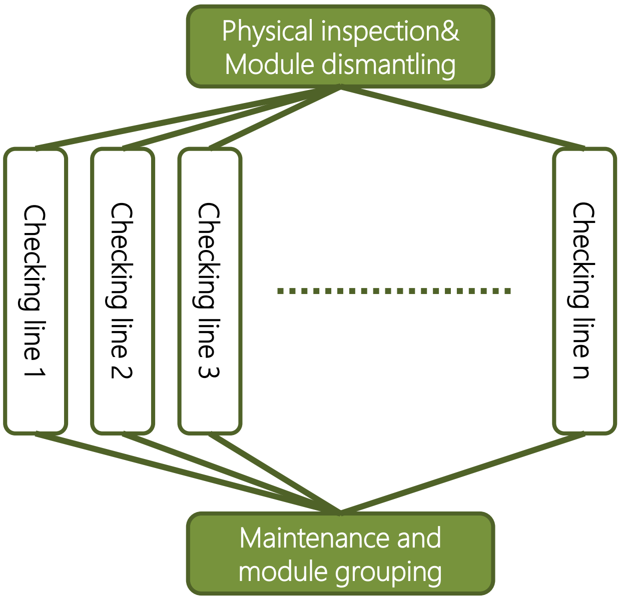


Figure 6.4: Duplicity of battery test benches or lines schema.

On the other hand, for module reconfiguration, the working on battery time is 14.75 h for PHEV or 25,15 h for EV. In this case, for an EV battery almost the same time is used in preparing the battery and in testing it, meaning that workers are saturated. Then, if we want battery tests benches duplicity to provide time reductions, the dismounting and mounting operations should be done by different operators. If two workers are contracted per turn, up to three lines could be installed for PHEV and two for EV batteries.

Many combinations can be studied regarding these options but reality should not escape from our scope. Taking a look at the number of registered cars in Spain (Fig.6.1) it can be appreciated that the bestselling model delivered just 388 cars (almost one car per day). That means that, from now until 10 years, no more than that will arrive yearly to the rehabilitation factory. That is why we had chosen two approaches, one for the first steps, when there are not many batteries, and another one considering a high capacity rehabilitation factory.

The economical results are shown in Fig.6.5. It can be appreciated that at higher capacities, the costs of rehabilitated batteries is reduced. It can also be noticed that direct reuse is always cheaper than reworked batteries under similar productivity environment. The best prices are 122 € /kWh from PHEV batteries and 87 € from EV.

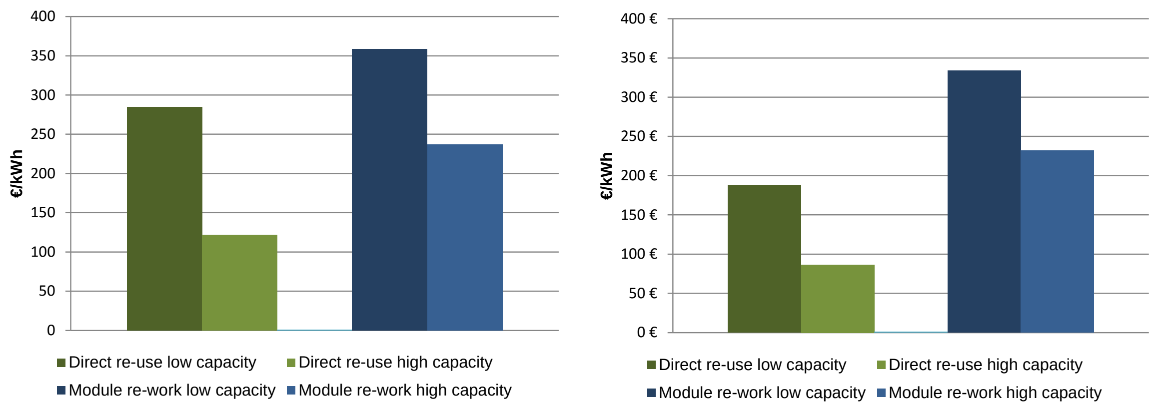


Figure 6.5: Cost per kWh of rehabilitated PHEV (left) and EV (right) second life batteries.

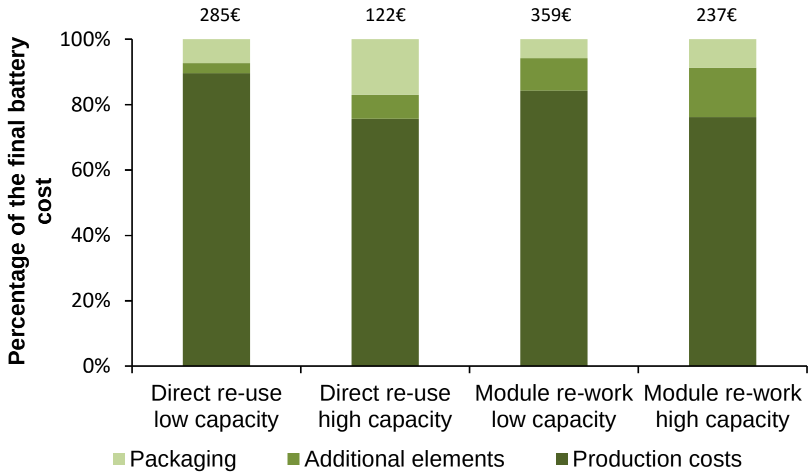


Figure 6.6: PHEV Battery total cost distribution.

Packaging and maintenance have fixed costs, that is, they do not depend on the strategy followed. Hence, when entering more into the cost detail distribution (Fig.6.6), it is visible that their impact is heavier in the high capacity options. It is also understandable that the module re-working strategy needs more materials to build a “new” battery, thus, higher costs and bigger impact. Of course, the production costs take the bigger part in all four studied cases, being always above 70% of the total.

Finally, looking at the production costs (Fig.6.7), it is visible that the impact of labor costs, investments amortizations and other costs (electricity, maintenance, etc.) also change along the strategy and productivity solution chosen. Obviously, labor costs are more determining in low capacity solutions than in more capable alternatives, where investments take the lead. For example, direct reuse in a high capacity configuration, which has up to six test lines in parallel, has an investment impact above the 50% of the final production cost.

A list of installation needs is presented in order to better understand the investments involved in second-life battery reconfiguration: Climate chambers, High power and energy testing equipment, prepared warehouses and storage racks, conveyors, forklifts, office equipment and industrial plant annual rent.

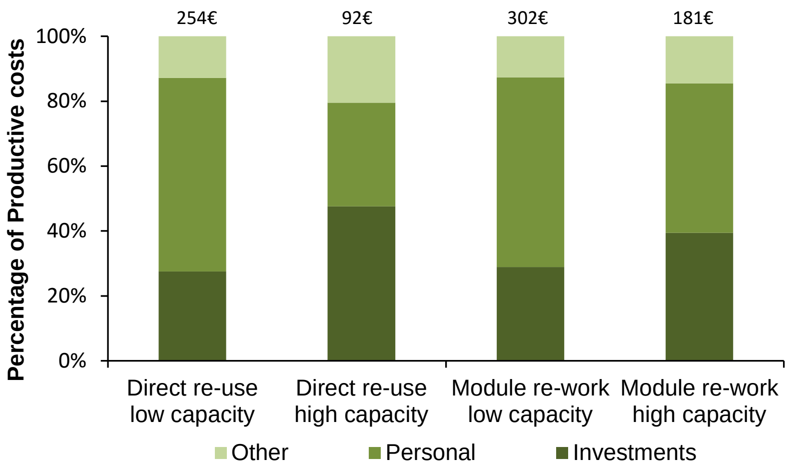


Figure 6.7: Distribution of PHEV productive rehabilitation costs for each solution.

In the end, it is evidenced that the faster production goes, the lower the price becomes and the smaller labor cost impact is. It is also visible that the cost reductions are more visible in direct reuse.

6.6 Conclusions

Nowadays, new batteries cost near 800 € /kWh and the expected prices for 2020 are around 400 € /kWh [47], [74].

The costs of rehabilitated batteries, no matter which strategy is followed, are always under 360 € /kWh. The best price obtained is 87 € /kWh from direct reuse of EV batteries on a high capacity factory. Indeed, it is 4 times cheaper than a low capacity re-worked one.

If the number of received batteries is expected to stay above the 500 units per year, it is highly probable to have profitable businesses. The difference from our best price and the expected cost of brand new ones is four times lower. That represents a substantial potential for second use batteries to have a niche in the energy storage market.

Anyhow, we can conclude that it is better not to count much on the module reconfiguration strategy, at least at the beginning, because there is not enough margin between the re-purposed cost and the expected price from new batteries. In fact, the direct reuse solution clearly takes the lead.

We can also affirm that EV batteries provide better economic results than PHEV ones because they have more modules, thus, more capacity in relation to the time invested in the process.

This first approach shows that results get better when more EV batteries are available. In fact, even the most intensive solution presented has a major manual work. Industrialization can easily provide lower costs if there are enough re-manufactured batteries to invest in.

Another expected improvement will surely come with a more efficient battery SOH assessment test, which is something car manufacturers are already working on. Actually, car manufacturers are also working on the development of a BMS prepared for first and second uses which will facilitate their integration in the net.

From the obtained results, we can suggest that reused batteries will speed up the entrance of storage systems into grid ancillary services.

Chapter 7

SOH determination

En 1937 murió John D. Rockefeller, dueño del mundo, rey del petróleo, fundador de la Standard Oil Company.

Había vivido casi un siglo.

En la autopsia, no se encontró ningún escrúpulo.

Eduardo Galeano "*Los hijos de los días*".

7.1 Motivation

The term SOH has been repeatedly mentioned all along this thesis and it has been reported, in chapters 4 & 6, as an essential parameter concerning batteries' 2^{nd} life applications.

By itself, the SOH defines the battery capacity at any moment in relation to the initial capacity. In the introduction it has been mentioned that it is used to determine the moment when the battery is not suitable anymore for traction purposes (SOH=80%-70%). That is the departing SOH for their 2^{nd} life.

Thus, the evolution of SOH or its fast or slow decrease, derives into the identification of the RUL and, consequently, the possible warranty that car manufacturers may offer. This lifespan warranty is the first aspect that the stationary business actors ask. RUL brings security in the investment and facilitates its introduction into the market. Thus, in order to properly calculate the RUL, to offer an accurate warranty and to proceed with the business cases analysis, it is important to precisely determine this SOH.

There are many methods to determine SOH, such as the Coulomb counting, Capacity Tests, Internal Resistance determination, EIS, Voltage characterization, Heating response, Battery cell unbalance, Relation between variation of SOC against Battery Voltage (dSOC/dOCV) or Change of a Battery equivalent capacitor (Ceff), but most of them require precise and expensive equipment or have an important error. Nonetheless, the standards used to test EV batteries are normally focused on the Capacity and internal resistance Tests or the EIS methodology, which are all time consuming and expensive, as reported in Chapter 6.

One possible option to accelerate this SOH determination and reduce the re-purposing costs would be to use the information stored inside the BMS memory. This means that the SOH should be calculated during the EV use with on-board data. This is exactly what the following chapter suggests by developing a novel approach for SOH assessment.

This novel SOH assessment is based on the recuperation voltage (or capacitance response). It was developed using the battery information gathered during years in the twin-drive PHEV project fleet from SEAT. It took several months of data harvesting and parameters comparisons until the relation between aging and voltage recovery was found and the method was presented as something new in the article entitled: *PHEV battery aging study using voltage recovery and internal resistance from On-board data*, published in the IEEE Transactions on Vehicular Technology journal the 28th July 2015, DOI:10.1109/TVT.2015.2459760.

The analysis and results obtained from this innovative SOH methodology are presented in this Chapter 7.

7.2 Introduction

Similar to mobile phones and laptops, the Lithium-ion batteries of EV and PHEV, lose capacity and power along time and usage [22]. In small devices this is not so problematic, because battery replacement is affordable, devices can still work connected to the power plug and, normally, technology evolution is so fast that most people replace the whole device when the battery depletes [98]. On the contrary EV batteries cost thousands of dollars, thus replacement is not foreseen [74]. A battery for traction services is considered inappropriate when it has lost about 20% of its unaltered capacity.

This capacity loss has been studied in many laboratories for different types of cells and under different controlled conditions [105]. Repeating specific tests after a number of cycles or months makes parameters tendency relatively simple to identify and, consequently, this information paves the way to the estimation of the SOH [35, 37]. Unfortunately, conditions in a vehicle are not so repetitive and controlled. Not only the way the vehicle is driven or the temperature influence on the SOH, but it also depends on the state in which the car is getting charged, if it stays parked for long periods of time or where does most of the driving take place (city, landscape, highway). Each of these aspects affect the battery in different ways and may lead to non-desired chemical reactions [106]. Thus, it is very difficult to find a common situation that provides robust and reliable parameters to estimate the SOH.

It is important to know the battery SOH in order to calculate, for example, the mileage range of an EV with a full charged battery or the necessity to replace the battery at the end of its lifetime. Battery life-length is something that car manufacturers are really concerned about, in order to keep the 8 to 10 year battery warranty. For this reason, many researches and engineers are implementing all sorts of algorithms in their BMS [60]. These algorithms go from the simple coulomb counting [107] to more complicated methodologies like support vector machine techniques [26] or statistic tools like particle filter [55] amongst others [108].

In this study, we have analyzed the aging effects during one year of use on a PHEV in Spain. We focused on two battery characteristics: Internal resistance R_i and the switch off voltage recovery $V_{recovery}$. In contrast to Kalman-filter or black-box, which are online techniques, the on-board data analysis has been done offline, as the information was gathered and the vehicle fleet already dismantled. However, the implementation of the presented methodology can be integrated in online systems.

7.3 Methodology

Temperature, voltage, current and energy exchanges are the parameters mostly used to track the battery behavior. Based on these four parameters, this study focuses the attention on two derived variables to delve into the battery aging analysis using on-board data: R_i and $V_{recovery}$.

7.3.1 R_i calculation

Normally to calculate the R_i of lithium batteries in laboratories, the Ohm's law is applied after a specific current flow during 2, 10 and 18 seconds [62] with the methodology described in Fig.3.16 from Chapter 3. As these specific conditions are impossible to obtain while driving due to traffic unpredictability, the ratio between the delta voltage and current after one second was used in eq.7.1 [109], even though the results will be less accurate.

$$R_i = \frac{V}{I} = \frac{\Delta V}{\Delta I} = \frac{V_t - V_{(t-1)}}{I_t - I_{(t-1)}} \tag{7.1}$$

In order to reduce the errors resulting from small denominator values $(I_t - I_{(t-1)})$, the only R_i values that have been taken into account, come from current drops of at least 20 A: $\Delta I \geq 20$. With this method, hundreds of R_i values were obtained per trip (considering long enough trips to discharge the battery by more than a 60% DOD).

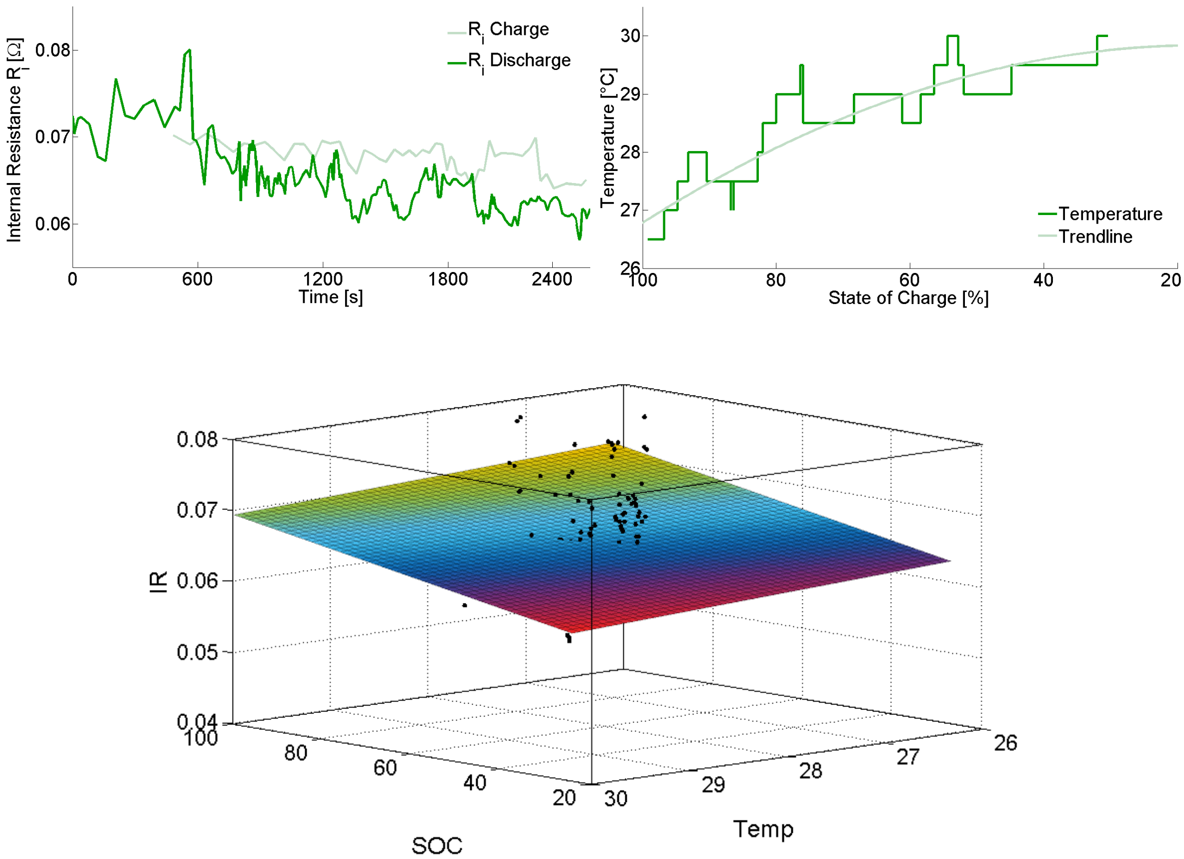


Figure 7.1: Top left: Evolution of filtered R_i charge and discharge against time during one trip. Top Right: Evolution of the temperature against SOC (SOC decreases along a trip). Bottom: 3D representation of the Evolution of filtered R_i under discharge against SOC and Temperature along a trip.

In Fig.7.1 (top-left) the differences between charge and discharge on internal resistance are appreciable after processing these values using a moving average [63]. Bibliography reported that at higher SOC and temperature, cells have higher potential activity, hence, lower internal resistance [95]. Since Fig.7.1 (top-left) shows that R_i reduces along a trip and, consequently against SOC, it means that temperature and SOC should play an important role. The relation between battery SOC and temperature (Fig.7.1, top-right)shows that, effectively, temperature increases during the trip. Additionally, Fig.7.1 (bottom) presents the relations of R_i against SOC and temperature in a 3D perspective for that specific trip. It can be appreciated that the effect of 4 ^oC is almost half the effect of 75 SOC percentiles, which means that temperature has a higher influence onto the internal resistance than SOC. This fact was also observed by Huria et. al. [110] when they defined that the R_i is composed of several resistances: Ohmic, charge-transfer, SEI, etc. and explained that some of them depend more on temperature than on SOC.

7.3.2 R_i and aging

To proceed with the EV battery R_i analysis along a year, an average R_i value per trip was taken. Then, these R_i values were first correlated with time, observing its particular behavior as trips were distributed randomly during a year. This same R_i correlation was done against the total capacity exchanged by the battery. As it will be seen in the results, nothing could be extracted from these two comparisons due to the fact that temperature has greater impact than aging on R_i and it varies a lot during a year. Finally the R_i was related to temperature in order to observe any clear tendency on aging.

7.3.3 Voltage recovery

A similar procedure was followed for the study of voltage recovery using EV on-board parameters. Four factors, described by eq.7.2, define battery voltage [62]:

$$V_{batt} = V_{equilibrium} + V_{resistance} + V_{reaction} + V_{diffusion} \tag{7.2}$$

$V_{resistance}$ represents the Ohmic voltage drop visible at the beginning of current flow, being the electrolyte resistance the major contributor. $V_{reaction}$ is principally caused by electrochemical and chemical reactions at inner surfaces. $V_{diffusion}$ is caused by a deficit or surplus of reactants. Finally the equilibrium voltage is the measurable battery voltage after a long period without use. As mentioned, the $V_{equilibrium}$ is not reached immediately after disconnection, there is a transition period and a voltage stabilization time, while the effects of reaction and diffusion progressively decrease [111].

From a theoretical point of view, the voltage relaxation could be used as an indirect measure of degree of lithiation in the cathode and anode of a Lithium-ion battery. This state of lithiation, in turn, determine the state of charge of a battery. Therefore, the relaxation trends, over the course of a battery life, keep changing as a consequence of lithiation states in the two electrodes. Additionally, during the battery use, there is a loss of active lithium mostly caused by the SEI growth and the side reactions seem to be the major cause during storage periods. [26]. Accordingly, if a battery voltage relaxation is compared under two identical operating conditions, the differences observed should be considered as an indicator of aging. In fact, this transition period between two battery load conditions (i.e. from active to paused) has been widely studied and there are also patents relating it with aging [112]. From now on, this effect will be defined as $V_{recovery}$.

When analyzing the driving data from the PHEV, the major problem was to find long enough pauses to observe the voltage evolution and having similar operating conditions that would lead to a possible aging correlation at the same time. In PHEV, this situation is found at the end of long trips, when the battery is fully discharged. In the specific case of the PHEV study, after the vehicles stops, the battery continues to transmit data during 5 minutes.

A $V_{recovery}$ example during these last 5 minutes is shown in Fig.7.2. It can be observed that it follows a logarithmic curve with different slopes on each measurement, never finishing above 2V.

The $V_{recovery}$ is calculated by subtracting the instantaneous positive voltage step V_{stop} at the current-cut and the battery voltage V_{5min} after 5 minutes from it, as described by eq.7.3:

$$V_{recovery} = V_{5min} - V_{stop} \tag{7.3}$$

The $V_{recovery}$ evolution has fast, medium and long time memory relations with current, SOC and voltage conditions previous to this transitory state. In this study, it is assumed that the $V_{recovery}$ starting conditions are similar. The V_{stop} and SOC are almost the same in all cases, due to the fact that the battery was discharged. Additionally the current flows before switch

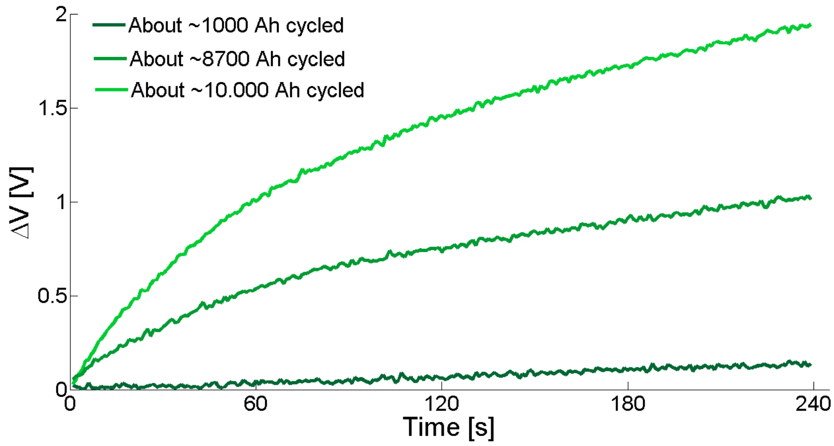


Figure 7.2: $V_{recovery}$ during 5 minutes after the EV stops for different trips. $V_{recovery}$ behaves different at different aging states during its lifetime.

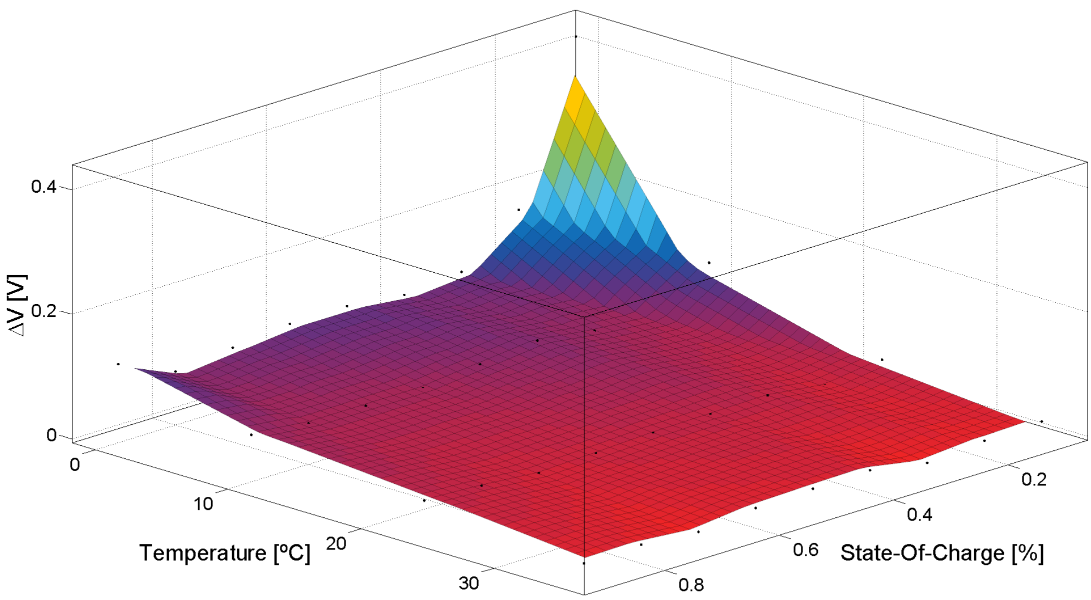


Figure 7.3: $V_{recovery}$ of a single cell 5 minutes after the discharge pulse at different temperatures and SOC points applying a pulse test at different SOCs in a climate chamber.

off are also similar in all cases. In fact, whenever a driver finishes a trip the car demands low current intensities during 15 to 100 seconds prior to the complete stop of the car. We observed that these currents were around 2 and 4 A. Therefore, we assumed that the fast and part of the medium memory dependency were alike for all trips.

As it happened with R_i, $V_{recovery}$ strongly depends on temperature. In fact, temperature is another factor to be taken into account when searching for the similar conditions needed to evaluate $V_{recovery}$. In order to determine the exact temperature effect on $V_{recovery}$, pulse tests at different temperatures and SOC using a single cell were executed under laboratory conditions. In our laboratory, the precise and fast measurement devices needed for this accurate test have a limited working voltage range from 0 to 18V. Therefore, we could not put the whole battery (280 – 370V) under test to evaluate the temperature effects. However, the results from the PHEV battery capacity test, done at the beginning and at the end of the project, showed that the different cells inside the battery had a similar SOH (with a difference lower than a 2% SOH). Additionally it has been checked that the cells response is similar by taking a look at the voltage evolution during the relaxation periods. These two facts allowed us to conclude that the study of a single cell to extract the temperature effect on the $V_{recovery}$ was robust enough. The tested cell is the same as those mounted in the PHEV battery, which are prismatic NMC cells with a nominal capacity of 40Ah. The $V_{recovery}$ response is presented on Fig.7.3 for temperatures of -18, 0, 10, 25 and 35ºC and in steps of 10% SOC.

There are two details to highlight from these responses:

- First, cold temperatures cause higher $V_{recovery}$, thus, lower responses and slower voltage stabilization.
- Second, around 70% SOC and 30% SOC, the $V_{recovery}$ is lower (either way, the voltage stabilization is faster), while in the edges, at 10 and 90% SOC, we find the worst responses. These results are directly related to the li-ion cell characteristic dSOC/dOCV peaks [113].

The usual lower discharge capacity limit for PHEV batteries is around 25%-30% SOC [114]. That is nearby the point where we took the voltage recovery data from the electric vehicle. Therefore, this is the SOC in which the cell thermal analysis was done. The equation related to $V_{recovery}$ and temperature is presented in section 7.4.

7.3.4 Voltage recovery and aging

To start with the analysis of the relations between $V_{recovery}$ and aging, the first thing to do was to calculate the $V_{recovery}$ for each trip by eq.7.3. This showed a dispersed cloud of points that should be arranged. As it has been already mentioned in section C, it is necessary to have similar conditions to evaluate the aging effects through $V_{recovery}$. Two methods were used to find these similar conditions: The first one was grouping the $V_{recovery}$ values from trips ending at similar temperatures. This showed a clear picture of the responses, but without much data per temperature range. The second method was the subtraction of the temperature correction using the equation found with the single cell characterization multiplied by the number of cells from the PHEV battery, as described by eq.7.4:

$$V_{recovery(corrected)} = V_{recovery} - n_{cell} \cdot V_{recovery(T)} \tag{7.4}$$

Where $V_{recovery}$ is the value obtained directly for each trip, n_{cell} is the number of cells in the battery, (84 in this case) and $V_{recovery}(T)$ is the voltage recovery correction factor at the temperature when the car stops.

This process allowed the evaluation of the impact of normal use on aging and a possible way to implement this new approach to the algorithms that evaluate the SOH with on-board data.

7.4 Results

This section describes the results obtained from the two derived variables aforementioned: R_i and $V_{recovery}$. As exposed in the methodology, each variable results will be presented separately.

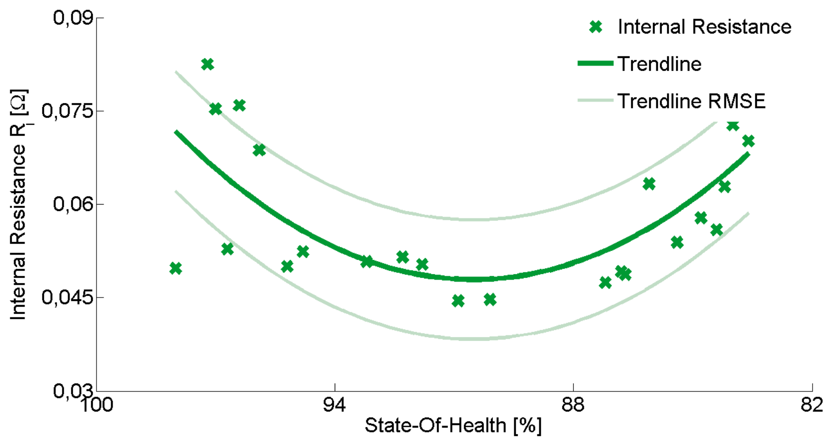
7.4.1 Internal resistance study

Literature reports that R_i increases with cell and battery aging [115]. To analyze if this parameter is useful for SOH determination with on-board data, a first comparison was done relating the R_i average per trip and the SOH of the battery. Instead of observing an ascending slope as the SOH decreased, it could be observed that this relation goes up and down independently; therefore, it showed that there was something more relevant than aging forcing this behavior (Fig.7.4, top).

Knowing that temperature is a key factor for internal resistance calculation, we took special attention on battery temperature and climate conditions over a year. Thus it was observed that the internal resistance values increased during winter and got much lower in summer.

As it can be seen in Fig.7.4, the internal resistance apparently has no correlation with the SOH. It was observed that the ambient temperature changed along time, being lower at the beginning and end of the tests and higher in the middle. To evaluate the Arrhenius-like temperature effect on R_i, in Fig.7.4-bottom, the temperature effect has been removed. As it can be seen the internal resistance stays almost constant against SOH until the end of life in the vehicle.

The 3D representation of both temperature and SOH (Fig.7.5) shows the effect of temperature as a major cause of battery R_i change, but it does not bring much information about any tendency of aging on R_i.



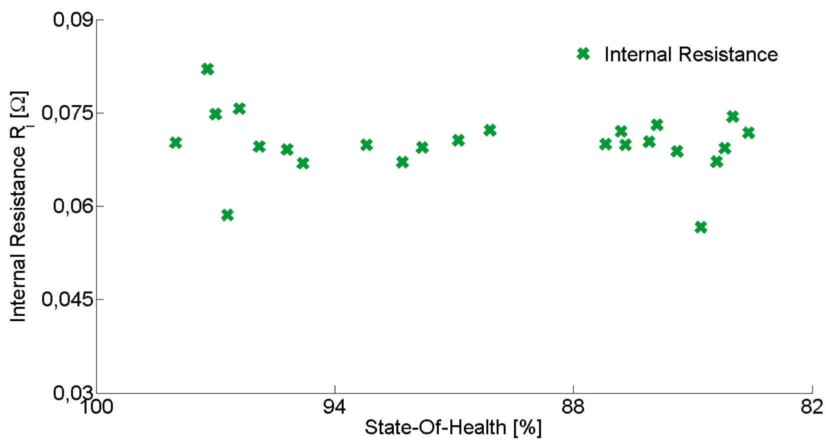


Figure 7.4: Average R_i evolution against SOH (Top); Average R_i evolution against SOH after temperature correction (Bottom).

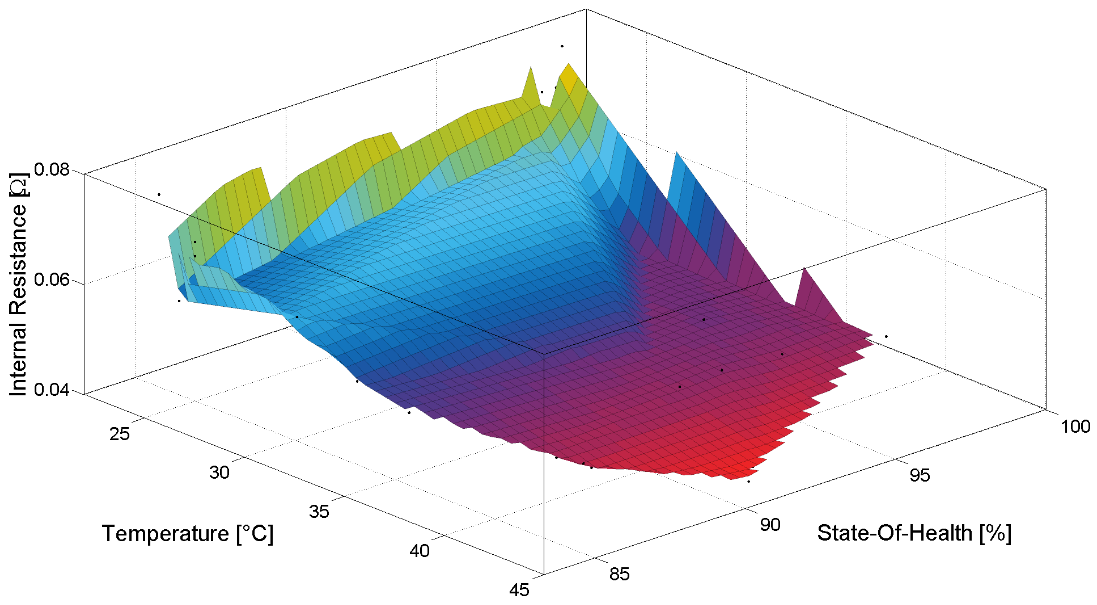


Figure 7.5: Average internal resistance per trip against Temperature and SOH.

7.4.2 Voltage recovery

As mentioned above, this second part of the results' section is focused on the analysis of $V_{recovery}$ during the last 5 minutes of the trips, when the car stops.

Like with the R_i, the first step was to find visible relationships between $V_{recovery}$, temperature and SOH with the data obtained from the vehicle. In Fig.7.6 its relation is presented in a 3D overview that demonstrates a weak but existent interaction between them.

An effective way to isolate the temperature effects on aging was achieved by grouping the $V_{recovery}$ values in 3 group of temperatures: 25, 30 and 40 $\pm$ 2ºC. The results are shown in Fig.7.7, where the aging effect is observable by the positive slope of the tendency curve. The temperature effect is also appreciable by the lower $V_{recovery}$ values at higher temperatures. It is also visible that at higher temperatures the dispersion is also lower and the correlation is

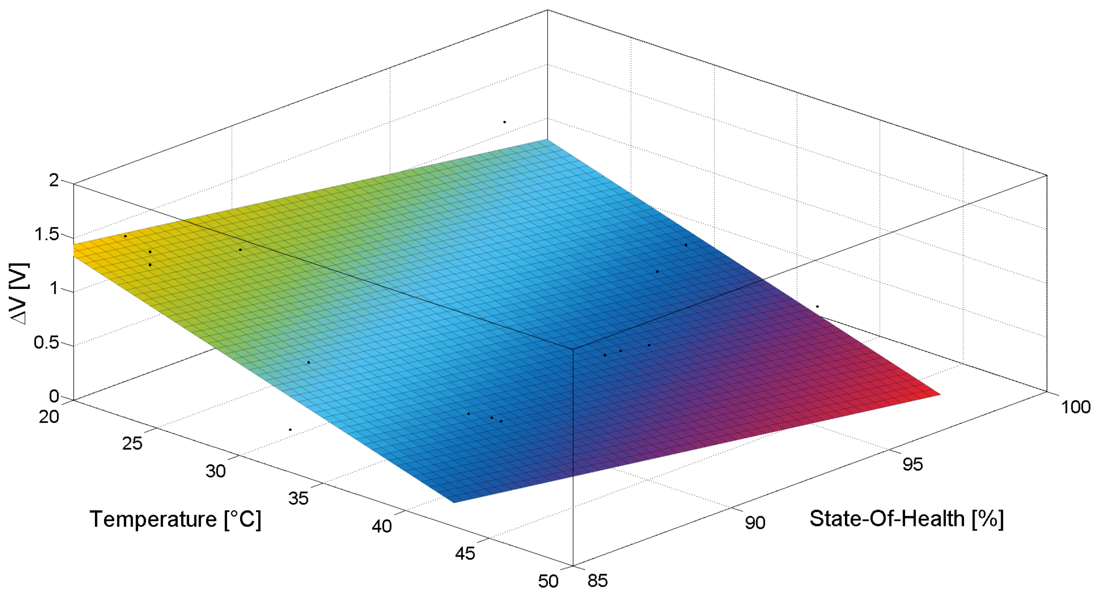
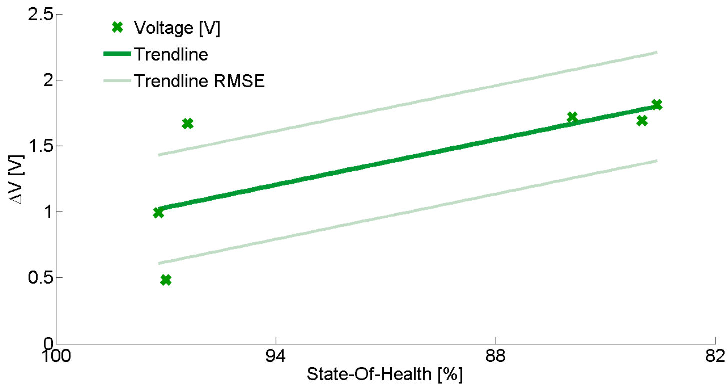
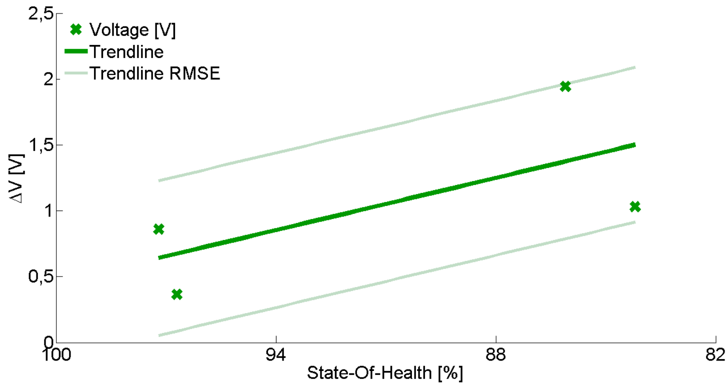


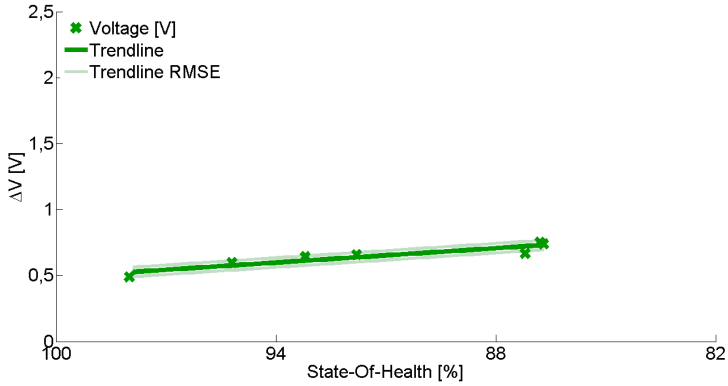
Figure 7.6: Linear tendency between Voltage recovery against temperature and SOH.



(a) 25 °C



(b) 30 °C



(c) 40 °C

Figure 7.7: Voltage recovery against SOH with linear interpolated trend line for determined temperatures at 25, 30 and 40 °C.

stronger. The few datapoints available for these specific temperature ranges and the dispersion derived from the acquisition of data every 1 second in the vehicle originate a severe variability at lower temperatures. However, the tendencies are noticeable.

The same relation is visible in the battery $V_{recovery}$ evolution during the 5 minutes when the car is harvesting data from the battery before completely switching off. The lighter-gray curves in Fig.7.8-top, which are the ones with lower SOH, demonstrate the above mentioned tendency and have higher voltage values than the ones that made less charge and discharge cycles.

In order to offer a useful algorithm for SOH calculation using $V_{recovery}$ with on-board data, a deeper analysis of the temperature effect was needed. It started with laboratory tests using a new single battery cell. After the characterization of $V_{recovery}$ at different temperatures and

SOC states presented in the methodology, the study was centered at the 30% SOC. This is the SOC where the $V_{recovery}$ is calculated using on-board data.

The laboratory equipment offers higher resolution and shorter time steps (in the PHEV the data was acquired every second). This fact allowed a more accurate observation of the $V_{recovery}$ evolution during the first seconds and minutes after cell disconnection. The $V_{recovery}$ evolution observable in Fig.7.8-middle confirms that at lower temperatures we obtain higher transition times to achieve the voltage stabilization, which means higher internal resistance and capacitance. Additionally, it can be noticed that it was during the first two seconds after cell disconnection, when there are the higher voltage differences. This means that, if the voltage recovery starts counting 1 or 2 seconds after the current cut, the differences encountered in the final value might differ up to a 50%, as it is shown in Fig.7.8-bottom. Hence, the growing variability of the $V_{recovery}$

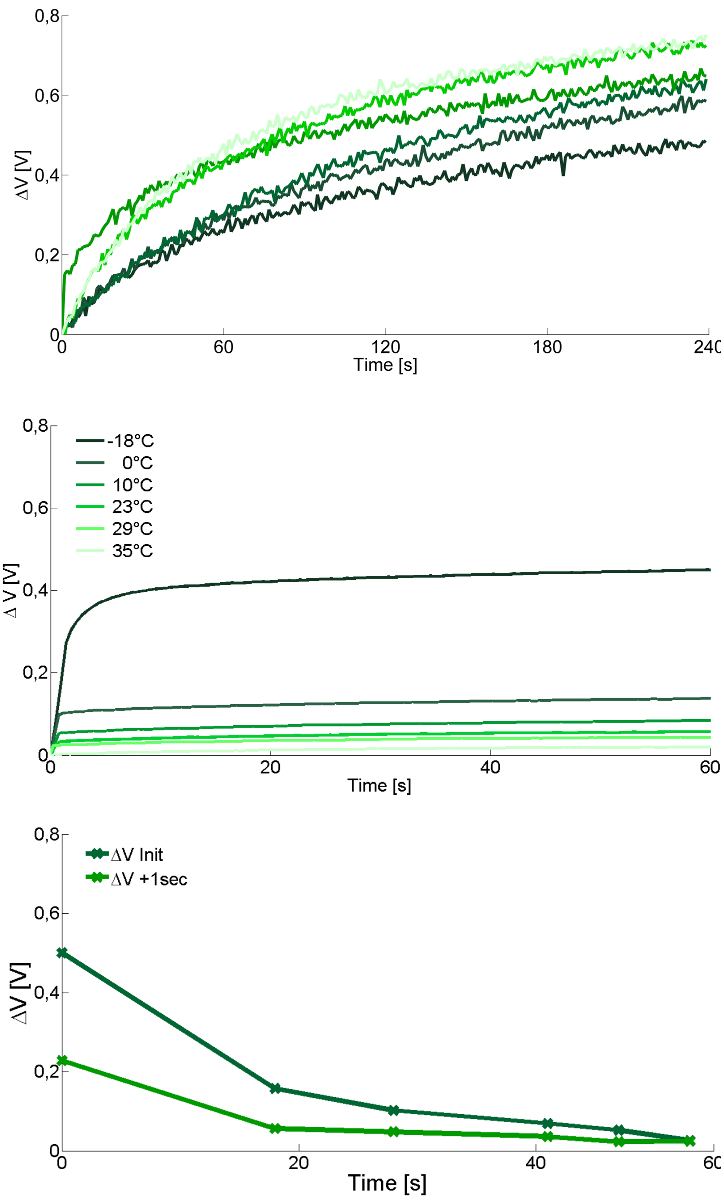


Figure 7.8: Top: $V_{recovery}$ evolution for 7 trips during 5 minutes after the car stops ending at 40ºC and different SOH. The lighter grey the lines are, the more energy exchanged though the battery. Middle: Voltage recovery behavior at different temperatures, showing the bigger variances during the first seconds. Bottom: 30 % SOC $V_{recovery}$ comparison starting one second after current cut.

values obtained at lower temperatures with on-board data can be explained by the fact that the data harvesting in the car is done every second. In any case, from Fig.7.8-middle, it was observed that the $V_{recovery}$ against temperature follows an exponential behaviour described by eq. 7.5.

$$V_{recovery}(T) = a \cdot e^{b \cdot T} \tag{7.5}$$

Where a = 147,95 and b = -0,0286 at 30% SOC for the analyzed cell. When exporting this analysis to other SOC or cell type, the parameters should be recalculated.

Eq.7.4 is used to eliminate the temperature effect on the $V_{recovery}$ calculation with the PHEV on-board data. The resulting $V_{recovery}$ values are denominated in this study as temperature corrected recovery voltage. The temperature corrected recovery voltage is presented in Fig.7.9-bottom, where, effectively, the dispersion is reduced compared to the bare $V_{recovery}$ values from Fig.7.9-top. Moreover, a light but linear increasing tendency that confirms the applicability of this tool for aging monitoring can be appreciated. Therefore, enclosing the temperature correction, the $V_{recovery}$ strategy can be included in SOH algorithms by integrating eq.7.6 with the trendline in Fig.7.9-bottom.

$$V_{recovery} = -0,28581 \cdot SOH + 3,0307 \tag{7.6}$$

The results during one year seem to provide some evidences of aging, however, considering that EV batteries are expected to last 8 years or more, the exposed theory and equation should be confirmed with the acquisition of more real driving data during longer periods of time.

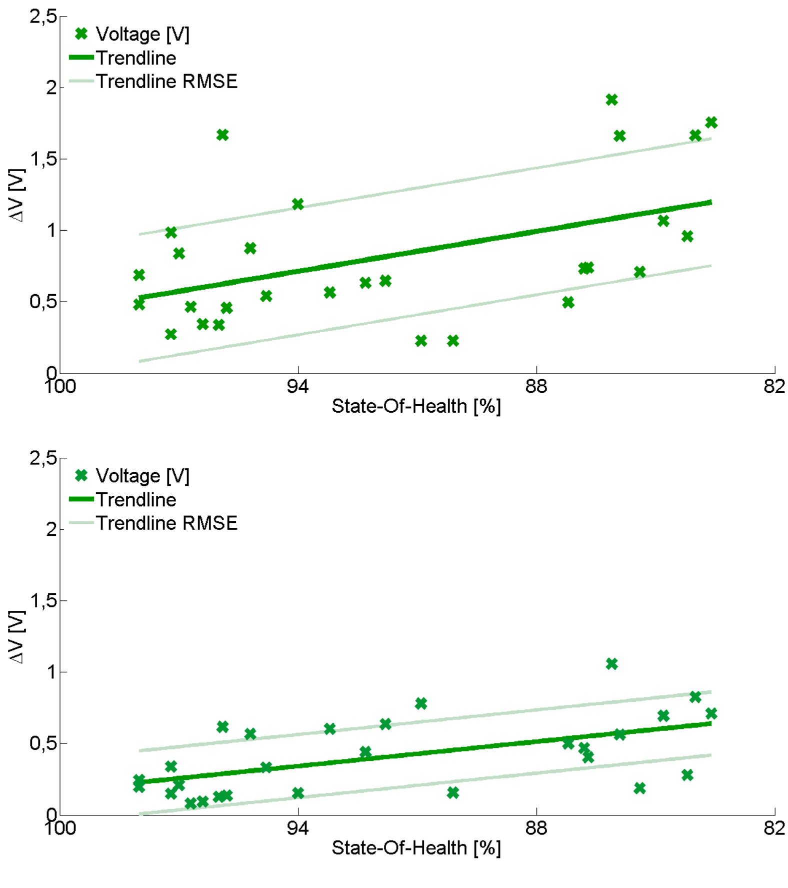


Figure 7.9: Bare $V_{recovery}$ values before temperature correction with on-board data (Top). Temperature corrected voltage recovery values using on-board data (bottom).

Additionally, results could be improved with the introduction of shorter on-board data harvesting time intervals. It has been proved that most of the variability of the obtained results came from the first second after the current-cut.

Finally, another option to obtain more robust results is giving more weight to the values obtained at higher temperatures (which offer better correlated results) and less weight to those obtained at lower temperatures.

7.5 Conclusion

Although under laboratory conditions the internal resistance is an aging monitoring parameter, the difficulties to obtain robust and accurate values from on-board data calculations, makes it not so interesting to follow for algorithms using on-board instant data from the EV.

In fact, when the battery reached the 82% SOH, the internal resistance was mostly affected by temperature changes rather than by aging.

On the contrary, at the end of the trips, the recovery voltage is foreseen as a key parameter for SOH assessments. If the recovery voltage is to be implemented in SOH algorithms, it should always consider temperature corrections in order to calculate the useful life prognosis of batteries more accurately.

Even though the results are encouraging, more data is needed to confirm and validate this preliminary approach. Indeed many alternatives to provide better results have already been proposed.

In this work it has been shown that it is possible to estimate the SOH of the vehicle battery systems with rough on-board data. To implement precise and detailed SOH algorithms using the $V_{recovery}$ methodology, multiple cell tests under laboratory accelerated aging conditions should be launched or more data from monitored cars has to be available.

Chapter 8

The Aging model and the expected Rest of Useful Time

"Il problema è che il mondo è un problema e certo non saremo noi a risolverlo".

Antonio Tabucchi, "*Sostiene Pereira*".

8.1 Motivation

Since now, this thesis presented the battery transformation needs for reuse, its re-manufacturing costs and a novel method to determine its SOH. However, in order to calculate the RUL and offer a valuable warranty to clients during its 2^{nd} life, an study of the aging of the battery beyond the 80-70% SOH and under the stationary applications requirements should be carried out.

To do so without waiting for battery failures to occur under real environment or in demonstration projects, which may take several years, an aging model representing the battery behavior must be used. Battery aging modeling offers faster results under all kind of working conditions.

Chapter 8 presents an aging model developed for batteries' 2^{nd} life RUL calculations based on generic information extracted from literature. This chapter describes how the aging factors are introduced in the electric circuit model. Then, it presents four 2^{nd} life case studies. Finally, the model simulates the aging of batteries under the 2^{nd} life working conditions and analyzes the RUL results in terms of time duration, energy exchange, cycles and economically.

This chapter is based on the article: *Modelo de envejecimiento de baterías de vehículo eléctrico reutilizadas para aplicaciones estacionarias*, presented in the XIX International Congress on Project Management and Engineering (CIDIP in spanish) that took place the on July $15-17^{th}$, 2015 at Granada. This publication was awarded with the *Accesit al Premio del Consejo General de Colegios Oficiales de Ingenieros Industriales.*

8.2 Introduction

The majority of sold EVs are equipped with Li-ion batteries to store energy [116]. As it occurs with laptops and other electronic equipment, these batteries degrade with time and use [22]. In the automotive world, it is considered that batteries are not useful for traction services when they have lost between a 20 and a 30% of its capacity [55]. This is the end of the 1st life and it is also the point at which most battery aging studies finish [68].

The EV is not profitable without fiscal incentives [117] mostly due to the elevated costs of batteries 700 € /kWh. Knowing that the integration of energy storage systems, to provide services to the electricity grid, is being more and more studied [16], [118], car manufacturers try to enhance the EV selling by re-selling their batteries at the end of the 1st life. In fact, some 2nd life battery projects have already appeared, as the EVEREST or the Second Life Battery project among others. Moreover, many papers and reports have been presented that study its economical viability [119], [41] and even some companies were created with this aim, as it is the case of 4R-energy.

All these projects try to demonstrate the technical feasibility of the EV battery re-use to store energy. At the same time, they expect to determine their batteries RUL in order to be able to offer credible guarantees. This last concept, the RUL determination during their 2nd life, is what will be addressed in this chapter by means of an equivalent electric circuit model of the battery.

Many authors have extensively studied dynamic battery models. There are simple models using only one resistance (R) and a resistance and capacitor pair in parallel (RC) [108] [120], or more complex models using Change Phase materials and coils [121], [25]. However, the base of these models is the same: the addition of elements into the model incorporate functional particularities and the results accuracy is improved [122].

These models are completed by adding the aging effects in order to determine the RUL under certain loads. As already analyzed in Chapter 3, the main aging factors are: Temperature (T), DOD, SOC and intensity rate (C-rate) [26], [30], [23].

These batteries age either while stored (Calendar aging) or under use (Cycling aging). In the first case, apart from time itself, there are two other factors that take part in the battery aging: Temperature and SOC. The temperature effect follows an exponential behavior described by the Arrhenius equation. On the other hand, the SOC effect, which may also be integrated using the battery voltage, has a linear effect [123], [36].

The cycling aging has two additional parameters to consider: DOD and C-rate [124]. DOD effect follows a logarithmic relation, while the C-rate effect is described by a second degree polynomial expression [10], [125].

In practice, these relations have two main consequences: An internal resistance increase (R_0) and a loss of capacity [6]. Although there are other effects on the RC pairs regarding the instant response of a battery, as it has been observed in the $V_{recovery}$ behavior in Chapter 7, they are not relevant for RUL estimations and will not be implemented in this thesis.

As the empiric experimentation with batteries for each possible application requires much time and it is expensive, a simulation will be done using a battery equivalent electric model parametrized using literature and experimental data from laboratory tests. The results of the simulations will provide an illustrative lifespan of batteries under different loads in a fast and economic way.

8.3 Objective

The main goal of this chapter is to determine, using an electrochemical model, the estimated lifespan or durability of a battery in different 2nd life applications. These applications will be classified in four groups regarding the characteristics of the battery loads.

The estimated RUL will serve to define and program battery replacements, study its impact in the amortizations and analyze the business cost analysis.

8.4 Methodology

For the RUL calculation, an electric equivalent circuit with a resistance and 4 RC pairs in series will be used, as shown in Fig.8.1. The OCV element represents a voltage source that establishes the OCV of a battery in relation to SOC. These parameters are normally taken from the battery manufacturer datasheet.

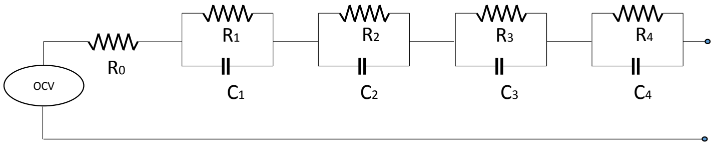


Figure 8.1: Electrochemical circuit used in this thesis with a resistance and four RC pairs in series.

Equations 8.1 and 8.2 describe the calendar and cycling capacity loss in function of the aging factors aforementioned.

$$C_{loss_{cal}} = f(V, T, t) \tag{8.1}$$

$$C_{loss_{cyc}} = f(I, V, DOD, T, t) \tag{8.2}$$

Regarding the Calendar capacity fade, the temperature, the SOC or voltage (V) and time (t) effects are mathematically translated into equation 8.3.

$$C_{loss_{cal}} = (\beta_1 + \beta_2 \cdot V) \cdot 10^6 \cdot e^{\frac{\beta_3}{T}} \cdot \sqrt{t} \tag{8.3}$$

On the other hand, the cell cycling capacity fade has, additionally, the current (C-rate or I) and the DOD effects. The capacity fade rate of the model is based on the degradation observed under continuous discharge and charge cycles at 1C (being 1C the current intensity corresponding to complete discharge of a battery in one hour), 273ºK, 50% average SOC and 100% DOD. Equations 8.4, 8.5, 8.6 & 8.7 are implemented in the model to adjust the degradation in relation to the aging factors.

$$I_{ef} = \theta_1 \cdot I^2 + \theta_2 \cdot I + \theta_3 \tag{8.4}$$

$$V_{ef} = \theta_4 \cdot V + \theta_5 \tag{8.5}$$

$$DOD_{ef} = \frac{log_{10}(DOD)}{2} \tag{8.6}$$

$$T_{ef} = \frac{e^{\frac{\theta_6}{T}}}{e^{\frac{\theta_6}{298}}} \tag{8.7}$$

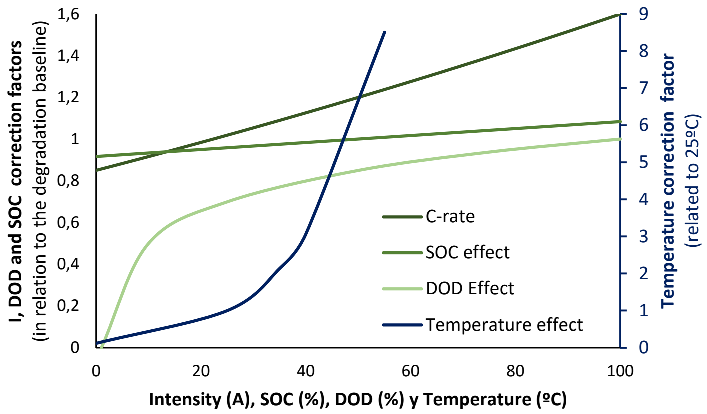


Figure 8.2: Effects of the different aging factors in relation to the baseline discharge rate at 25°C, 1C and 100% DOD cycles.

Where the parameters $4\beta_1$, β_2, β_3, θ_1, θ_2, θ_3, θ_4, θ_5 & θ_6 should be determined for each battery type. In the case under study, a graphic representation of these equations is presented in Fig.8.2.

The electrochemical model was developed using MATLAB® and its Simulink® tools and libraries. A block-like schematic representation of the model is presented in Fig. 8.3.

The model inputs are the current loads and temperature, which are defined by the use cases in 2^{nd} life applications. When they enter into the model, it calculates the electrical instant response of the battery, providing the following outputs: Voltage (V), SOC and DOD variations, Capacity fade, SOH and internal resistance R_0 increase. These outputs are then re-introduced into the model as feedback inputs for the subsequent iterations. This loop is necessary to obtain precise battery aging and performance responses.

Knowing that the main consequences of aging is the capacity loss, the state of health is then calculated as the ratio between the actual battery capacity (Cap_T) and the initial battery

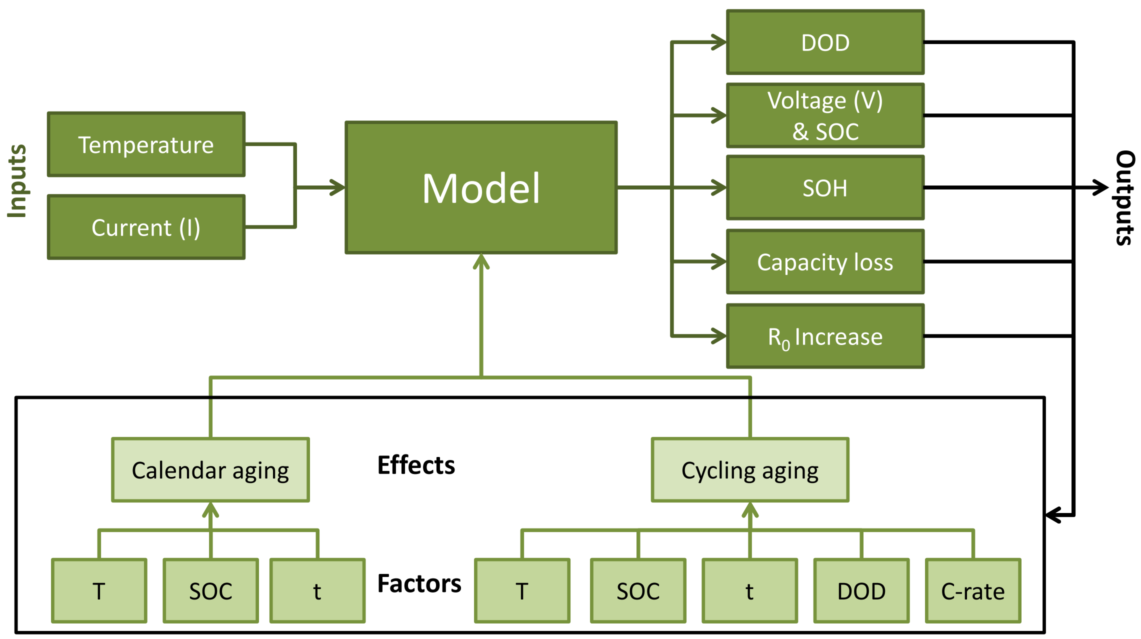


Figure 8.3: Block-like schema of the electrochemical model.

capacity (Cap_i) as expressed in eq.8.8. This will be further used to determine the functional end of the second life [60], [126].

$$SOH = \frac{Cap_T}{Cap_i} \tag{8.8}$$

Moreover, from empirical laboratory tests results, a second order polynomial expression (eq.8.9) was obtained relating the SOH with the internal resistance increase, or what is equivalent, the R_0 in the model from Fig.8.1. This polynomial relation is consistent compared to other studies with similar conclusions [127].

$$R_0 = \alpha_1 + \alpha_2 \cdot SOH + \alpha_3 \cdot SOH^2 \tag{8.9}$$

This R_0 value will be further used to determine the battery efficiency degradation and to quantify the energy loss (mostly caused by the Joule effect [94], [128]) of the battery (Q in equation 8.10. Obviously, the energy losses are higher at higher C-rate.

$$Q = R_0 \cdot I^2 \tag{8.10}$$

The moment when these batteries are not capable to offer the energy that each application needs is determined by simulating the battery performances, under different use cases and loads, using this model. The different load and use cases identified are:

- Self consumption in residential or commercial environments: These systems are based on the "peak shaving". The objective is to reduce the bill by storing energy during low tariff hours to use it at high tariff hours and, at the same time, reduce the contracted power. If there are renewable energy systems connected to the microgrid, the storage device can be used to store this energy when the production is higher than the demand. The system load simulated will be equivalent to daily full charge and discharge cycles. The energy considered for this simulation was taken from the average energy consumption in Spanish houses, which is 10 kWh/day.

- Island installations: In this case, as the system is not connected to the electricity grid, the energy storage device should be able to provide energy during the hours when there is no energy production. Additionally, it has to be over-dimensioned in order to ensure electricity power during three days, for the exceptional cases when energy production is not possible (i.e cloudy days for photo-voltaic systems). The same daily energy consumption than in the previous case was considered. Therefore, the energy storage system should have a capacity of 50 kWh. In this use case, the charge and discharge cycles have a 30% DOD.

- EV fast charge: The fast charge of EVs requires power levels close to 50 kW. When an EV starts to charge, the local network is stressed. This effect has been studied by [11], [71]. To eliminate it and to reduce the costs of these power level installations, the use of 2$^{\text{nd}}$ life storage devices to provide the additional power needed is analyzed. The 2$^{\text{nd}}$ life battery load follows a slow charge and a fast discharge cycle. The battery capacity considered for this application is the same as the one used in the EV, without any change, that is, 20 kWh. It will be assumed that two fast EV charges will be done daily.

- UPS: These type of systems are conceived to offer energy during 15 minutes until the electricity grid power is re-established or other power sources, such as diesel generators, are activated. They are often used in telecommunications and data centers, where sudden

Table 8.1: Simulation battery 2^{nd} life load cycle characteristics.

Application	Initial SOH	Final SOH	Initial DOD	C-rate	Avge. SOC
Self consumption	80%	40%	85%	C/20	50%
Island installation	80%	60%	30%	C/75	85%
Fast EV charge	80%	60%	85%	1.5C	82%
UPS	80%	60%	85%	2C	90%

stops are not conceivable. The battery load cycle follows a slow charge, then the battery system stays completely charged during long periods of time (10 days in this case) and then it suffers a fast discharge. Although the energy capacity of these systems may substantially change from one installation to another, in this case 10 kWh will be considered.

Table 8.1 summarizes the main characteristics of these applications used in the simulation. It should be emphasized that, on one side, all applications have an EoL when the battery achieves a 60% SOH except for the self-consumption case, where it goes until a 40% SOH. This particularity is given due to the fact that the capacity loss influences only in the revenue obtained and it is not functionally critical as it happens in other applications. On the other hand, the DOD used for the simulation is of a 85%, which is the limitation inherited from the EV battery pack for security and safety reasons.

It was considered that the batteries were placed in controlled and enclosed environments for the RUL calculations. Hence, the temperature changes were soft and away from extreme situations. Accordingly, two possibilities were analyzed in this study: A constant temperature case at 25^{o}C (298 K) and a temperature year cycle ranging from 10 to 30^{o}C (283 - 303 k) with $\pm$5^{o}C daily variations as shown in Fig.8.4. The first possibility considers that the temperature is controlled by active cooling and heating systems, while the second possibility has no temperature control. This was done to evaluate if there is a noticeable change in the RUL evolution with or without temperature control. It has to be taken into account that cooling systems consume energy and cost money, thus, it is preferable to avoid them.

On the economical side, from the results obtained in chapter 6 and from the study by Neubauer et al. [47] it is considered that the re-used battery price will be about 100 € /kWh. The battery acquisition cost is obtained by multiplying this value by the battery capacity (kWh) needed in each 2^{nd} life application. With this and the RUL results, the minimum amortization costs will be calculated.

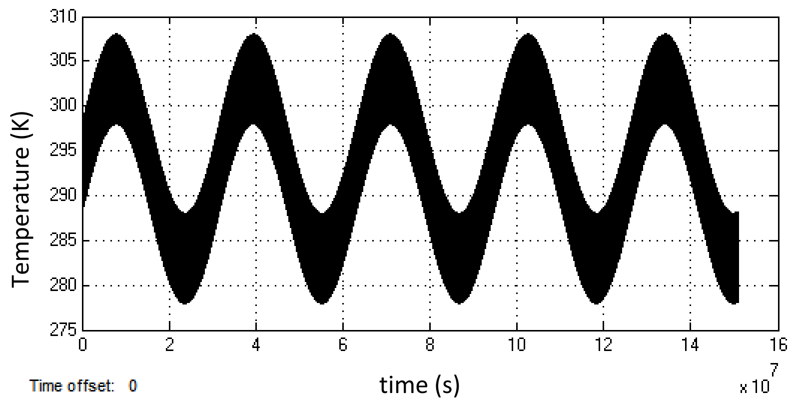


Figure 8.4: Annual temperature cycle with $\pm$ 5^{o}C daily variations.

8.5 Results

This section starts with the presentation of the SOH evolution resulting from the simulation at 25ºC constant temperature. The departing SOH is 80%, as it is considered that this could be the real state of health when batteries start their second life. Fig.8.5 shows, effectively, that the applications with higher C-rates and more frequent discharges, like the EV fast charge, age faster. In fact, the battery will last only 1.7 years on EV fast charge applications, while in less demanding applications, like UPS, it is expected that the battery lifespan will be longer than 24 years. Moreover, the next application with longer lifespan is the island installation, which is the one having lower C-rates. It has to be noticed that, as it is also appreciable in Fig.8.5, the final SOH for self-consumption applications is 40% and its RUL is almost doubled in comparison with finishing at 60%.

A deeper analysis of the results shows that the repartition of calendar and cycling aging impact is not constant. In fact, calendar degradation becomes more relevant as the battery RUL is longer. This is presented in Fig.8.6 in a bar diagram. Accordingly, it can be seen that the UPS and island applications, which are the ones with longer RUL, have a calendar aging impact of 27 and 18% respectively. On the other hand, the applications with less than 10 years lifespan have a cycling aging impact higher than 95%.

The results presented in Fig.8.7 allow us to identify which is the impact of the DOD and the C-rate on the quantity of cycles and accumulated capacity exchanged (Ah). The black line in Fig.8.7, that represents the total amount of accumulated capacity discharged, shows that the self-consumption application is the one with more energy exchanges. It should be noticed that its final SOH is 40% instead of 60%. The UPS application is the one doing fewer cycles and, although being the case with longer lifespan, it is the case in which less energy is exchanged, which corresponds to the results presented in Fig.8.6. This is explained basically because the battery cycles only during a 1,5% of the total lifespan and it rests fully charged afterwards. Additionally, when it finally is turned on, it does it under the highest current exigencies studied.

Fig.8.7 also shows the number of cycles that the batteries may do in these second life applications. Looking carefully to the complete equivalent cycles (which refers to translate the cycles done to 100% DOD cycles), it can be appreciated that the self-consumption does 2551 cycles, while the others do not achieve the 1.200 cycles or, for the worse performing case, the UPS finishes after doing only 785 complete cycles.

Using equation 8.9, the final R_0 results indicate that it has increased a 74%, reducing significantly the final battery efficiency.

When applying the variable temperature cycle, it can be observed that the RUL increases around a 20% in all the studied cases. Additionally, it should be noticed that the SOH evolution

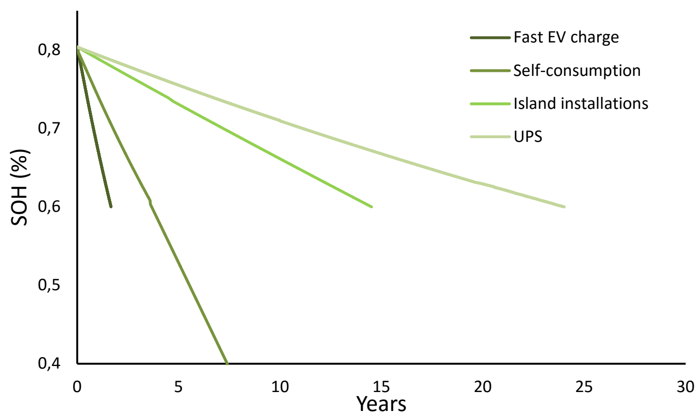


Figure 8.5: Battery SOH evolution under different 2^{nd} life applications at 25ºC.

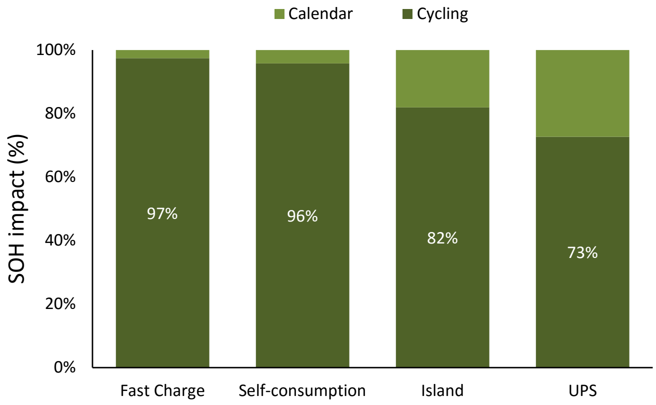


Figure 8.6: Impact of the cycling and calendar aging on the final SOH.

has a sinusoidal behavior, which corresponds to the annual temperature cycle. However, the daily temperature cycle is not appreciable. These results are shown in Fig.8.8.

The longer lifespan is explained due to the fact that the working temperature passes more than 2/3 of time below 25ºC. Obviously, if these premises change, the results will change accordingly.

This longer RUL has a direct effect on the cost analysis, affecting the maintenance intervention and the investment amortization.

Table 8.2 reflects the aforementioned economic impact of RUL changes for each application. For example, for fast EV charging applications with controlled temperature, it is obtained that we need to replace the batteries in less than 2 years, which implies 1200 € per year in amortization to be able to have enough cash to buy new batteries when it is needed. Additionally, the amortization is presented in relation to the kWh installed, in order to evaluate the costs per energy storage unit.

It should be noted that, contrarily to other applications, the UPS has a great capacity variability, which goes from few kWh to MWh. 10 kWh were taken in this study to have a similar order of magnitude with the rest of applications.

Additionally, Table 8.2 allows the comparison of the obtained results with and without temperature control. Therefore, considering the amortizations all along the battery lifespan, it can be appreciated that their value is lowered by the lifespan enlargement due to the non-controlled

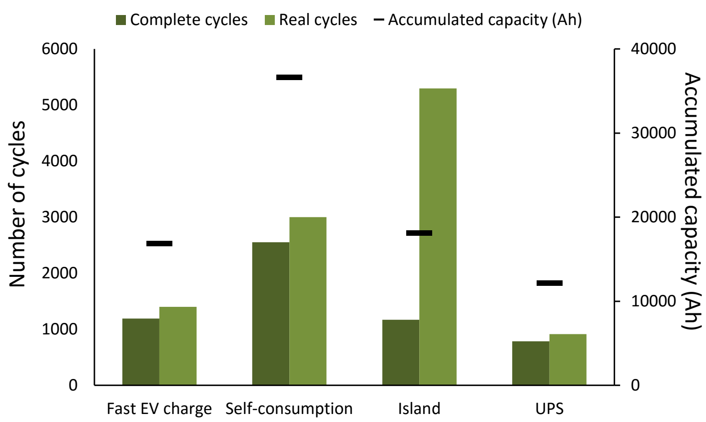


Figure 8.7: Number of cycles done per battery and total accumulated capacity discharged for each 2nd life application.

Table 8.2: Results and cost summary

	Fast EV Charge	Self consumption	Islanded	UPS
At 25 °C				
Lifespan (years)	1,7	7,4	14,5	24
Minimum battery capacity(kWh)	20	10	50	10
Battery cost (€)	2000	1000	5000	1000
Minimum yearly amortization (€)	1199	135	345	42
Minimum amortization per kWh (€ /kWh)	60	14	7	4
No temperature control				
Lifespan (years)	2	9,3	17,9	28,6
Minimum battery capacity (kWh)	20	10	50	10
Battery cost (€)	2000	1000	5000	1000
Minimum yearly amortization (€)	994	107	279	35
Minimum amortization per kWh (€ /kWh)	50	11	6	4
Reduction	**17%**	**20%**	**19%**	**16%**

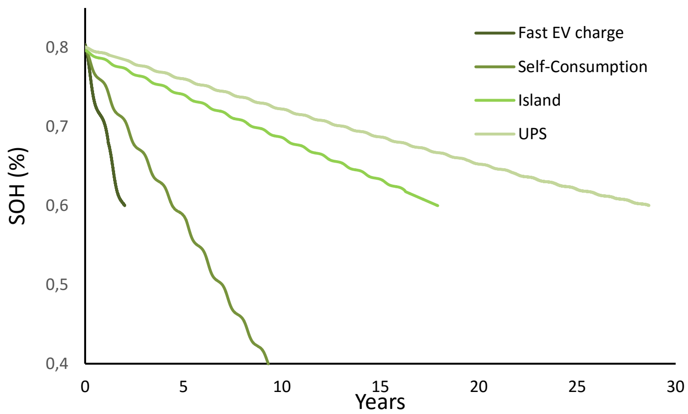


Figure 8.8: Battery SOH evolution under different 2^{nd} life applications at variable temperature.

temperature cycle between 10 - 30 °C in relation to the 25 °C controlled case. In fact, these reductions may reach the 20% in the best case.

8.6 Conclusions

The economic viability of using batteries to store energy depends enormously on the battery price and lifespan.

The use of 2^{nd} life batteries allows a reduction of the first term, the battery price, being necessary to evaluate the durability of these batteries in stationary applications.

This chapter showed how the battery lifespan not only depends on the number of cycles but also in the working conditions. Hence, the battery lifespan goes from 1,7 years in the case of Fast EV charge applications and almost up to 29 years in UPS applications.

One of the key factors affecting the battery lifespan is temperature. Therefore, it has been evaluated that the battery life length is enlarged by a 20% if the temperature oscillates between 10 and 30 °C instead of being controlled and fixed at 25 °C using air cooling systems.

Consequently, it has been concluded that there is no need to include active cooling and heating systems in the battery location if it stays within this range of temperatures. This reverts in an important investment reduction (no need to purchase and install this system) and an improvement of efficiency and functional costs as no energy will be used to cool down the room. In fact, not controlling the room temperature reverts in a reduction between a 15 and a 20% of the battery amortizations for replacement due to the useful life enlargement.

These aforementioned amortization costs oscillate between 1.200 and the 994 € per year in EV fast charge applications, while it reaches only 42 - 35 € /year in UPS applications. Additionally, self-consumption and island applications require annual amortizations around 120 and 300 € respectively.

Finally, the applications with heavier working conditions have lower duration and fewer cycles. Thus, if better results are foreseen, studies based on oversized systems bringing lower C-rates and DOD should be carried out until the optimum result between initial investments and business revenues are obtained.

The presented battery aging model allows the evaluation, in a short period of time and with precision, of the expected RUL of batteries under different working conditions, which is necessary to correctly evaluate the corresponding business models using energy storage systems.

Chapter 9

Aging Electric Model description

"Mais le monde est changé à cause de l'usage qui en font les humains".

Wajdi Mouawad "*Anima*".

9.1 Motivation

In the Chapter 8 the reader could observe the relevance and value of having a precise model to obtain the RUL. Chapter 9 intends to bring a deeper knowledge of the development phases of the proposed aging model.

This chapter exposes the assumptions that where taken during its formulation; which limitations the model has; how the different aging factors are included in it and the platform and software used to run the simulations.

Additionally, the reasons for selecting one or another parameter or expression in the model and how they are developed using the MATLAB® and Simulink® tools is exposed in this chapter.

The reasoning will use some of the images and information from the presentation *"Sunbatt: Use of a Second Life Battery System from PHEV in Stationary Applications"* given by members of Institut de Recerca en Energia de Catalunya (IREC) in the "Smart City Expo World Congress: The smart place to be" that took place in Barcelona in November 2015. This presentation should be considered as a result and dissemination of the Sunbatt project [18].

Moreover, this chapter will end up with the implementation of the model using energy load curves that have a closer approach to real grid or photo-voltaic systems requirements. These load curves were provided by IREC within the scope of the Sunbatt project too. The results were presented in the *"Energy businesses from re-used electric vehicle batteries"* at the "Global Cleaner Production and Sustainable Consumption Conference: Accelerating Transitions to Equitable and Sustainable Societies", that took place in Sitges the 3rd November 2015.

9.2 Introduction to the model

As already presented in Chapter 3 (Fig.3.18) and in Chapter 8 (Fig.8.1) the electric equivalent model is based on a resistance and 4 RC pairs in series.

The main idea of this model is to use the temperature and battery current loads as inputs to obtain the aging effects and, consequently, the SOH evolution and RUL that will be used afterwards for business analysis. This concept is described schematically in Fig.9.1. The "Battery" represents the *electrochemical model*, the *DOD, SOC, SOH, Capacity Loss and Internal Resistance Increase* are the outputs that will re-enter in the model as aging factors (including the calendar and cycling aging) closing a loop that will result in a final RUL estimation.

To facilitate the comprehension and use of the model, it is described through different layers or subsystems, departing from a general overview in the first layer, while reaching more detailed subsystems beyond in the following layers.

The first layer is presented in Fig.9.2, where the inputs, a battery cell and the overall voltage output are shown.

The Current input (on the left side in Fig.9.2) refers to the current flowing through the equivalent circuit elements, while the Temperature (coming from the top in Fig.9.2) is used to determine the precise values of the elements in the circuit, as the Resistance and RC pairs values change with temperature that will be described in the second layer subsystem.

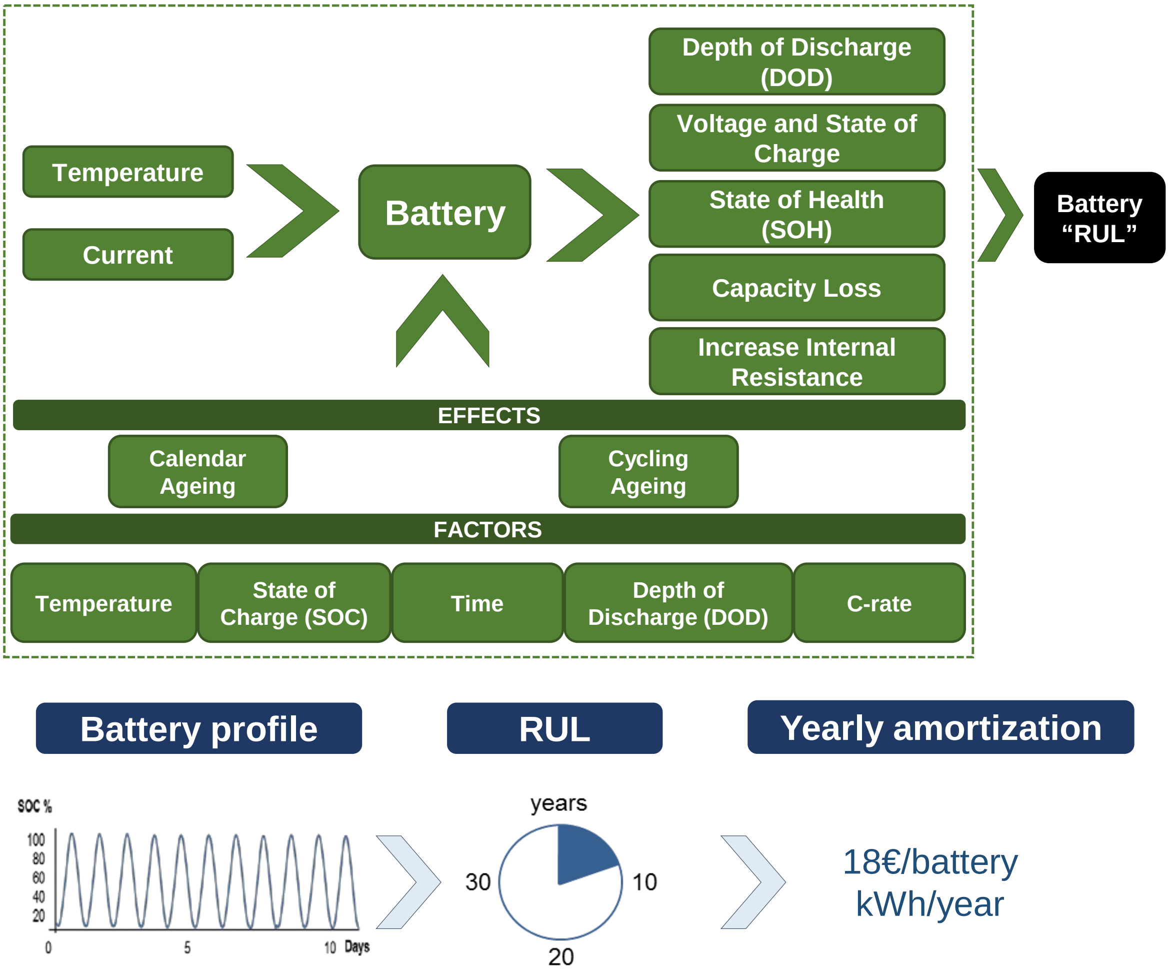


Figure 9.1: Aging Model and RUL schema.
Source: Canals et al. [92]

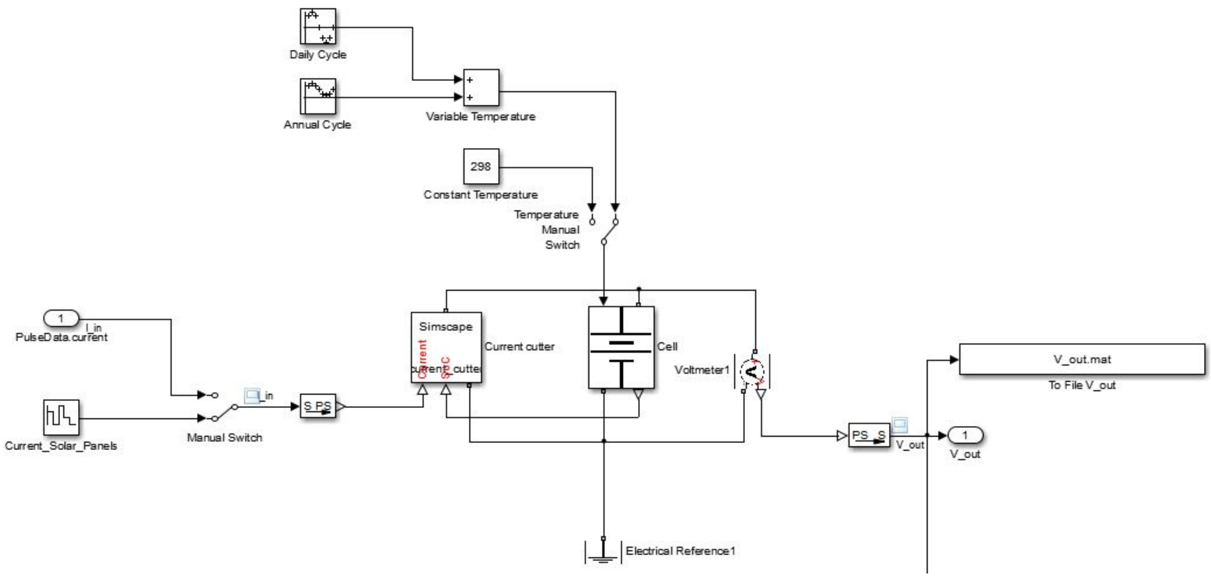


Figure 9.2: First layer or system block diagram. Screenshot from Matlab®.

The aforementioned inputs of the model (temperature and current) are directly introduced into the model using Constant, Signal Generators or Repeating Sequence blocks from Simulink® libraries.

For example, on top of Fig.9.2 the two possible temperature inputs (constant or annual temperature cycle) are visible. The selection of constant or cycling temperature inputs is done by means of the manual switch after them. A similar thing happens with the current inputs that are visible in the left side. A selection of the input current can be done. In Fig.9.2, two types of current inputs are represented: one taken from a datafile, corresponding to a pulse test that was used to validate the model response; and the other one given by a repeating Sequence Stair previously described. Additionally, there is a *current cutter* element, designed to eliminate the current signal in case the SOC of the battery goes above or below the functional limits of the EV battery (for example, below 0% SOC).

The voltage output is shown on the right side of Fig.9.2, obtained from the Voltmeter converter block. Finally, the cell block, which is the heart of the model, is found in the center of Fig.9.2. Here inside we will find the first subsystem/layer of the model.

9.3 The equivalent electric layer

The first thing visible in the second layer subsystem presented in Fig.9.3 is the equivalent electric circuit. This Simulink organization represents the the schema of the equivalent circuit model from Fig.8.1, with the resistance (red colored block) and the 4 RC pairs (green colored blocks).

The electric equivalent elements are defined as "*Resistor X*" or "*Capacitor X*", which have variable values. In fact, the "*From*" blocks that are found just before the resistances and capacitors (cyan colored blocks) correspond to the functional value of these elements at a determined SOC and Temperature that come from the look-up tables presented in Fig.9.4. As previously described, the values of this look-up tables were obtained fitting the curve response to the results taken from EIS testing at each SOC and Temperature done to individual cells under controlled conditions in the Volkswagen installations. Additionally, the resistances have their values multiplied by a "*resistance increase*" block (yellow colored). This resistance increase is caused by aging, as defined in Chapter 8, and its introduction will be described in the following sections. Hence, these elements have two inputs: the electric equivalent value coming from the look-up tables and the current passing through each element.

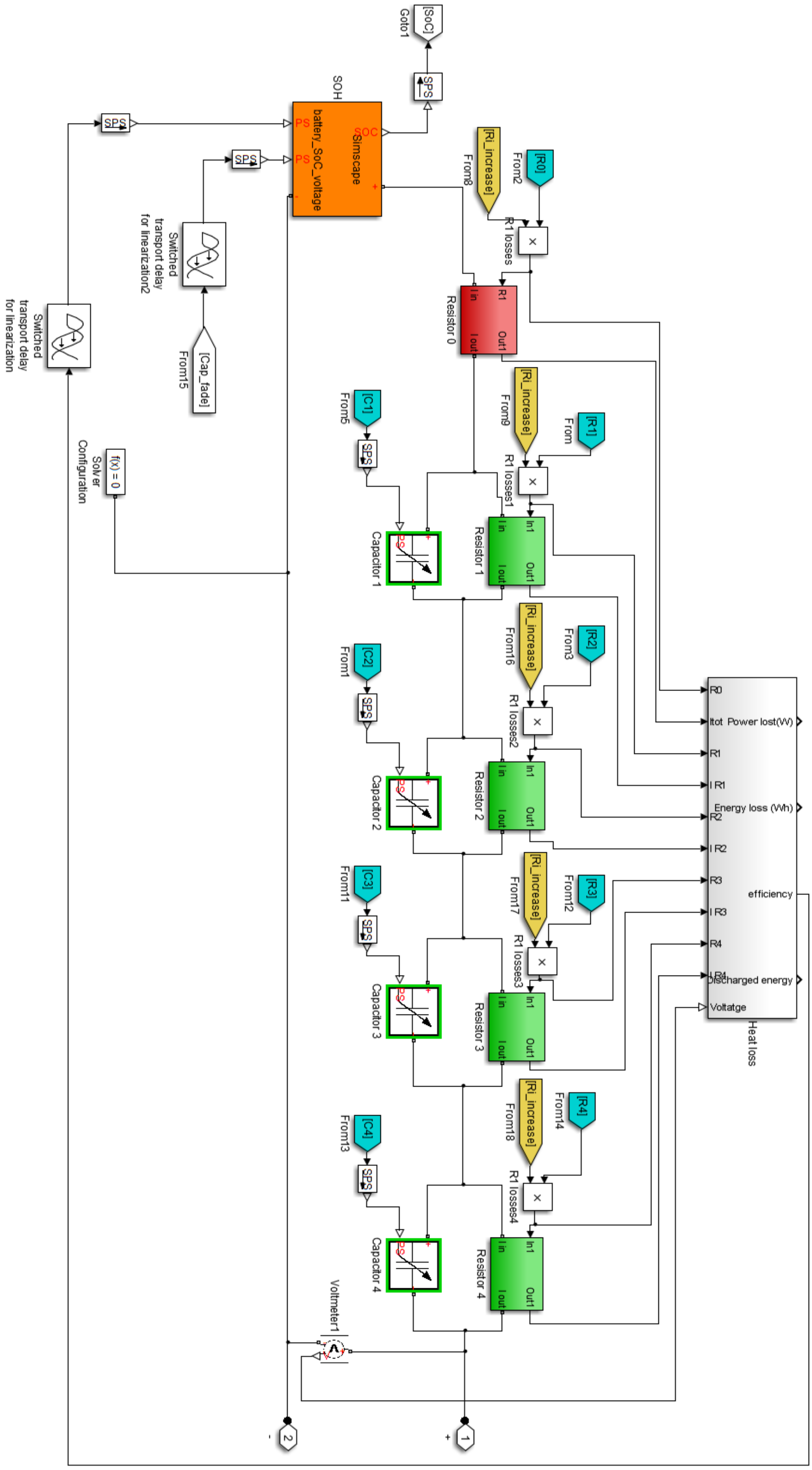


Figure 9.3: Second layer or system block diagram corresponding to the equivalent electric model. Screenshot from Matlab®.

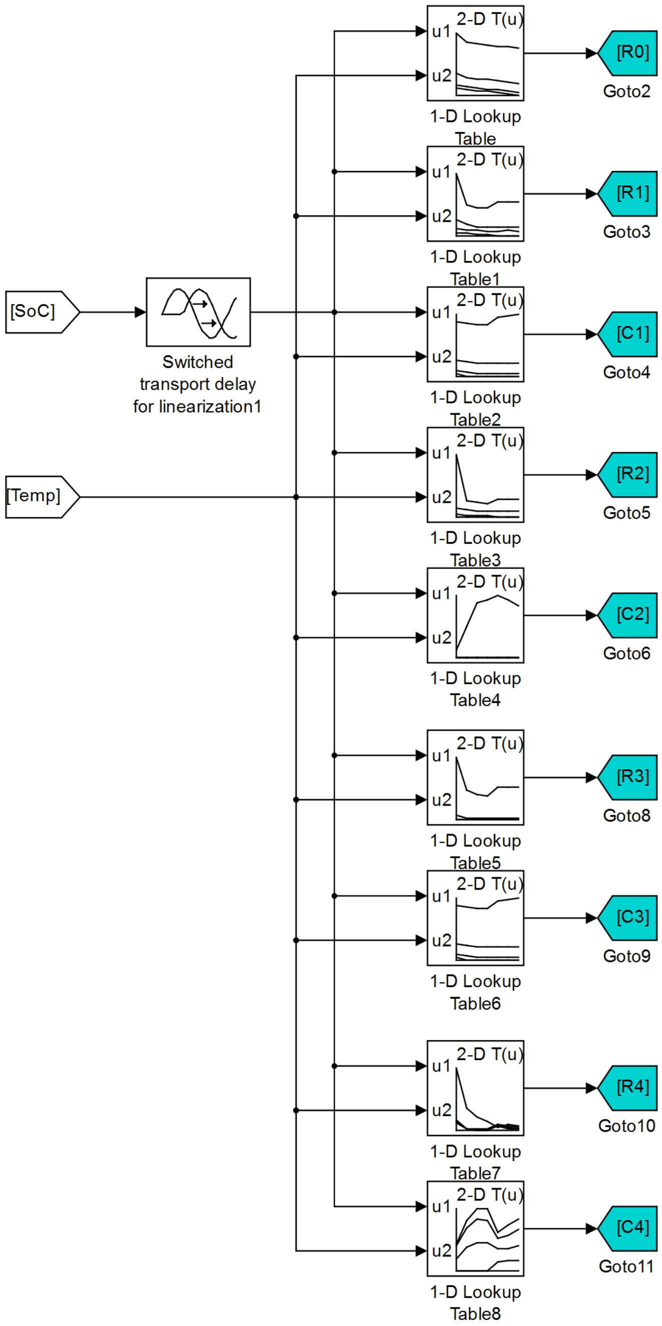


Figure 9.4: Resistance and Capacitors look-up tables from the second layer. Screenshot from Matlab®.

The output of the "*Resistor X*" or "*Capacitor X*" blocks is the current passing through it. Although the resistances in Fig.9.3 seem to have two outputs, they both refer to the same current output. In fact, one is the physical signal used in the by following elements, and the other is a conversion of this signal into a mathematical value that will be used to calculate the cell efficiency and energy losses due to the Joule effect. This calculations are executed in the subsystem called "*Heat Loss*" (grey block), which calculates the eq.8.10.

The last element to introduce is the OCV element or the power source. In this model it is found in the left side of Fig.9.3 defined as *SOH* block (orange colored). *SOH* block function is to calculate the remaining capacity of the cell, that is, the SOC that will be used to find the corresponding R and C values in the Look-up tables represented in Fig9.4. *SOH* block takes the battery initial capacity and SOC and counts the intensity passing through the circuit to calculate the SOC at every instant. A fine observer would have seen that it has 3 inputs:

- Current
- Efficiency
- SOH

These two inputs are used to calculate the total useful capacity of a cell considering the energy losses and the aging of the battery. It can be seen that the efficiency signal comes from the "*Heat Loss*" subsystem, while the SOH comes from the capacity fade calculation, which value is saved in the "*Cap fade*" variable or "From15" block.

9.4 The aging model

The aforementioned "*Cap fade*" variable is calculated using the equations described in Chapter 8. This section explains how they are introduced into the model using Simulink® tools.

The capacity fade or aging has been assumed to be the sum of the Calendar and the Cycling aging to the SOH of the battery at the start of the 2^{nd} life. These calculations are implemented by the two subsystems visible in Fig.9.5 (Magenta block for calendar aging and orange block for Cycling aging). The calculation of the capacity fade is done at each interval, and the result is added to the previous value, as presented by the blue delimited sum block with a delay loop from Fig.9.6. It should be understood as an integrator of time on a variable curve. The output of this calculation is the SOH and, as it can be noticed, the EoL corresponds to the Stop simulation block limiting the SOH decrease to a fixed value. These limits correspond to the 60 and 40% SOH respectively.

This SOH value is stored in the "*Cap fade*" Goto block that multiplies the nominal capacity of the battery to obtain the available or useful capacity in the next iteration loop of the model.

The other event that may stop the simulation occurs when the SOC goes below the working limit.

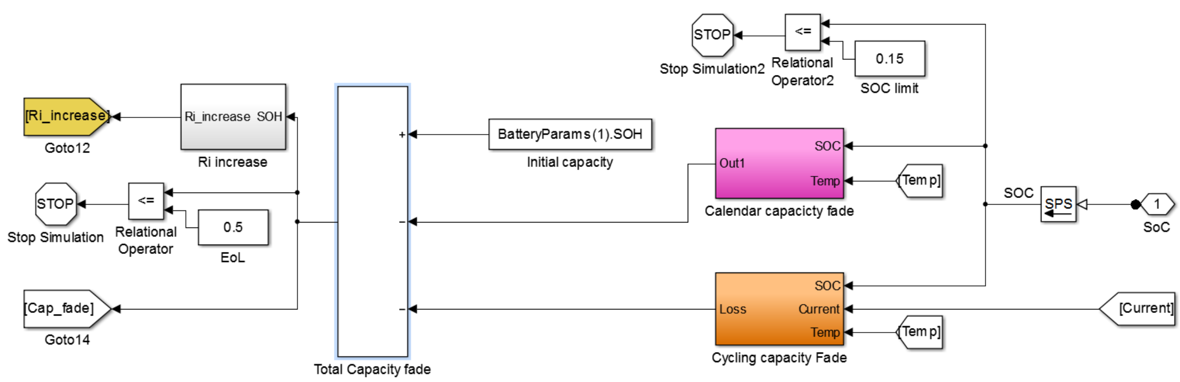


Figure 9.5: SOH or total capacity fade calculation system.
Screenshot from Matlab®.

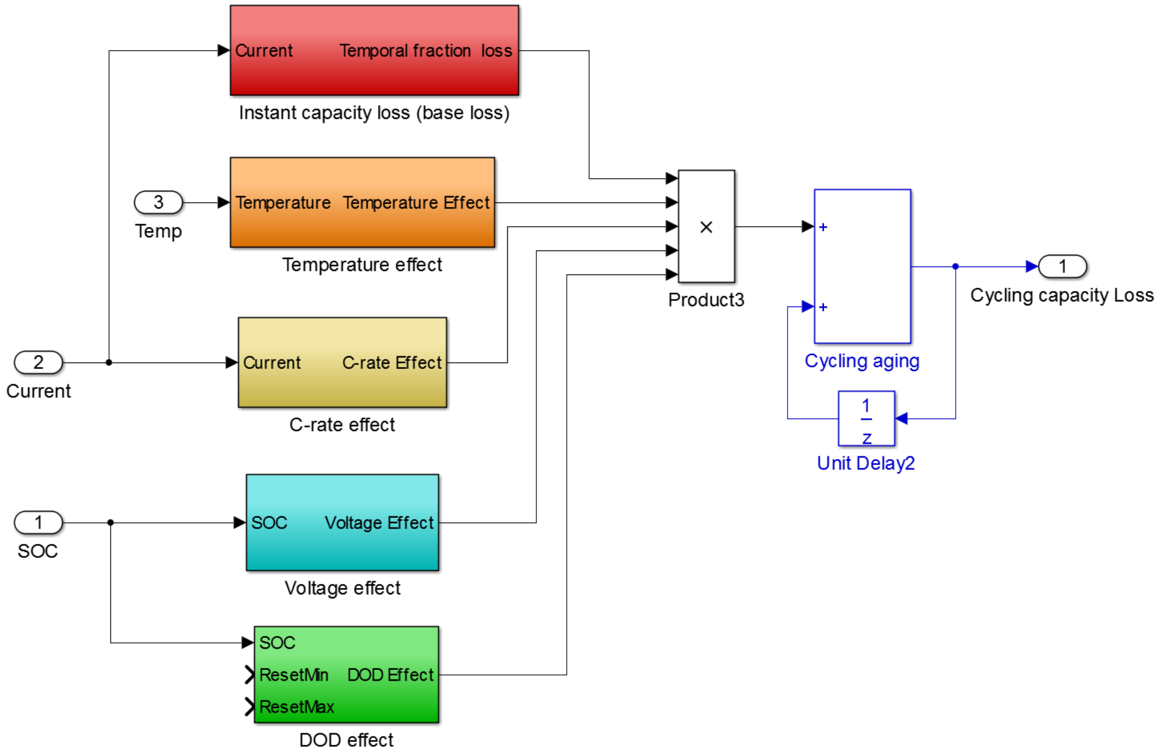


Figure 9.6: Cycling aging subsystem, with the SOH evolution base loss and the 4 correction factors.

Screenshot from Matlab®.

The calendar aging subsystem image is not printed because of its simplicity to implement it with the Simulink® libraries' mathematical blocks. However, it should be noticed that its inputs are SOC and Temperature. Additionally, as the calendar aging strongly depends on the time passed since the battery was build, it was assumed that the 1st life took 10 years. Clearly, it is not enough to introduce only the SOH into the model, we should include this time value in order to have an accurate RUL result. The simulation results may substantially differ depending on the years batteries had passed in the car before they are removed and prepared for stationary applications.

This calendar aging was calculated with the values obtained from the studies done in the SIMCAL project [36], by Schmalstieg [123] and by Stroe [64] in NMC cells as explained in Chapter 8.

Cycling aging has a particular way to be calculated. Previous works calculated the capacity fade effect according to the total amount of capacity (Ah) that passed through the battery (or Ah throughput) in relation to the different aging factors [129].

Although this model still relates the SOH evolution with the different aging factors, it works a little bit different. In fact, it takes the expected aging evolution from a 25Ah (1C) charge-discharge cycle, at 25ºC and a 100% DOD. This SOH evolution is called *instant capacity loss* or base loss (represented in a red block in Fig.9.6). Then, this value is corrected regarding the four aging factors calculated in four additional subsystems, which are shown in Fig.9.6:

- Temperature effect (Orange subsystem)
- C-rate effect (Yellow subsystem)
- Voltage (or SOC) effect (Cyan subsystem)
- DOD effect (Green subsystem)

These correction factors multiply the value from the baseline aging at each iteration.

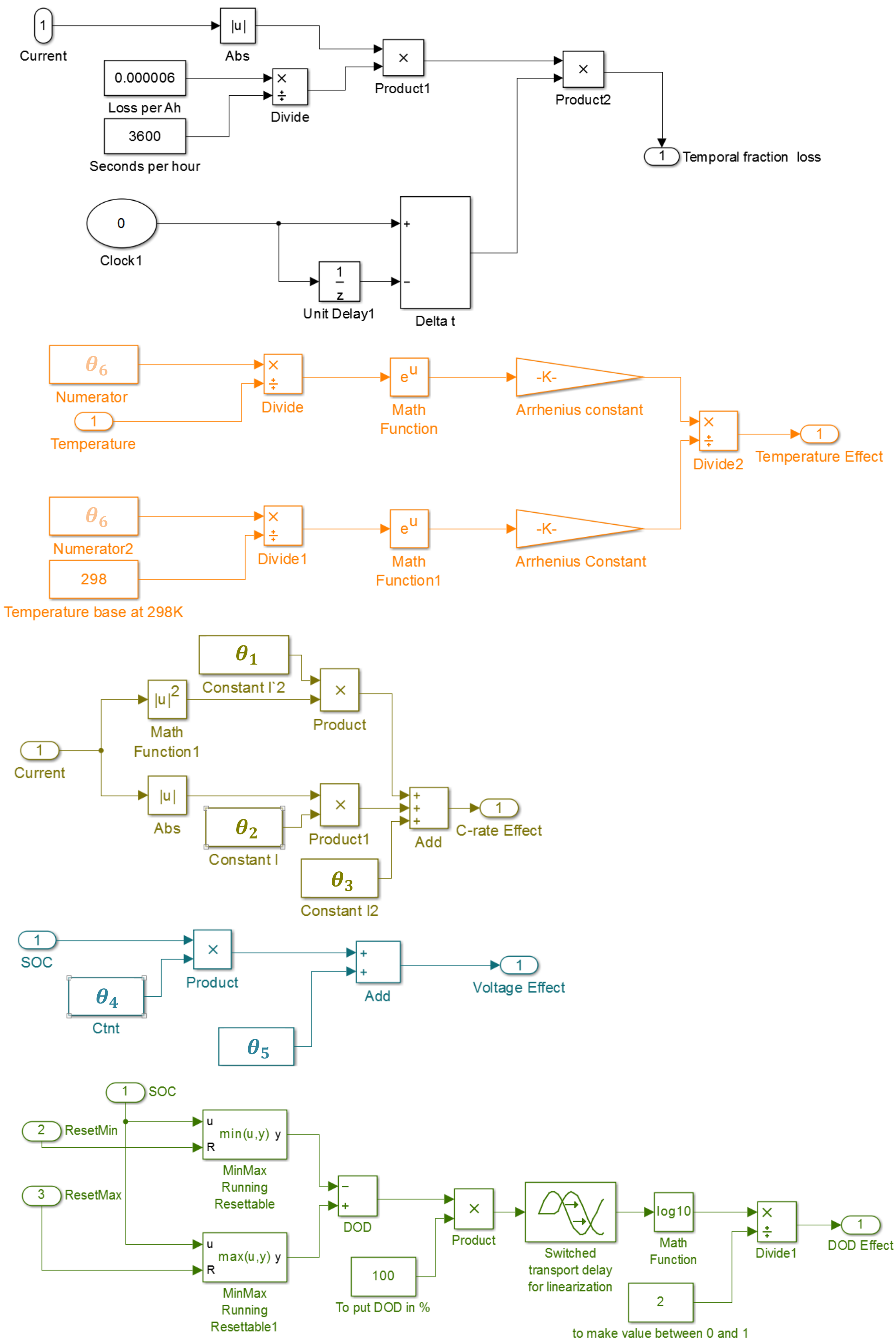


Figure 9.7: Base loss plus the 4 relating the aging factors as 4^{th} layer subsystems.

The instant capacity or base loss is calculated from [59], [34], [123], [36], [64]. Although the Ah throughput has been considered as a useful parameter to calculate aging [130], [131], in this model we took the current through the battery at each instant, which ends up with the same Ah throughput but uses time instead. In this way, aging continues even if there is no energy exchange, and the instant changes in the load profile (in DOD, or C-rates, etc.) are immediately covered.

Again, the 4th layer subsystems regarding the cycling aging factors described in chapter 8 by equations: eq.8.4, eq.8.5, eq.8.6 and eq.8.7 are simple to implement in Matlab with common math's blocks. They are presented in Fig.9.7 where the different coefficients from the mentioned equations are visible. It should be mentioned that some switched transport delay blocks had to be introduced in the DOD subsystem in order to eliminate loop incompatibilities, i.e. output signals needed previous input signals on other subsystems at the same timestep.

Finally, the polynomial function that describes the internal resistance increase (eq.8.9 presented in Chapter.8) was obtained from real tests on several battery cells. These cells were submitted to two different constant temperature storage (40 and 55^{o}C) and at different SOC (20, 40 60 80 and 100%). These test results and the parameters α_1, α_2 and α_3 from eq.8.9 are visible in Fig.9.8. It can be appreciated that the majority of cells follow the *Regression* curve no matter the temperature; however, the 4 cases at 100% SOC have another tendency with higher internal resistance increase rates. In this model, these 4 cases were no taken into consideration because the BMS in the battery pack does not allow the cells to reach the 100% SOC, they are restricted to 95% SOC maximum with the objective of enlarging the lifespan.

This model has, however, some limitations. For example, as sown in Fig.8.2, the model is not prepared to work at low temperatures below 0^{o}C. In fact, below 0^{o}C, eq.8.3 should change from

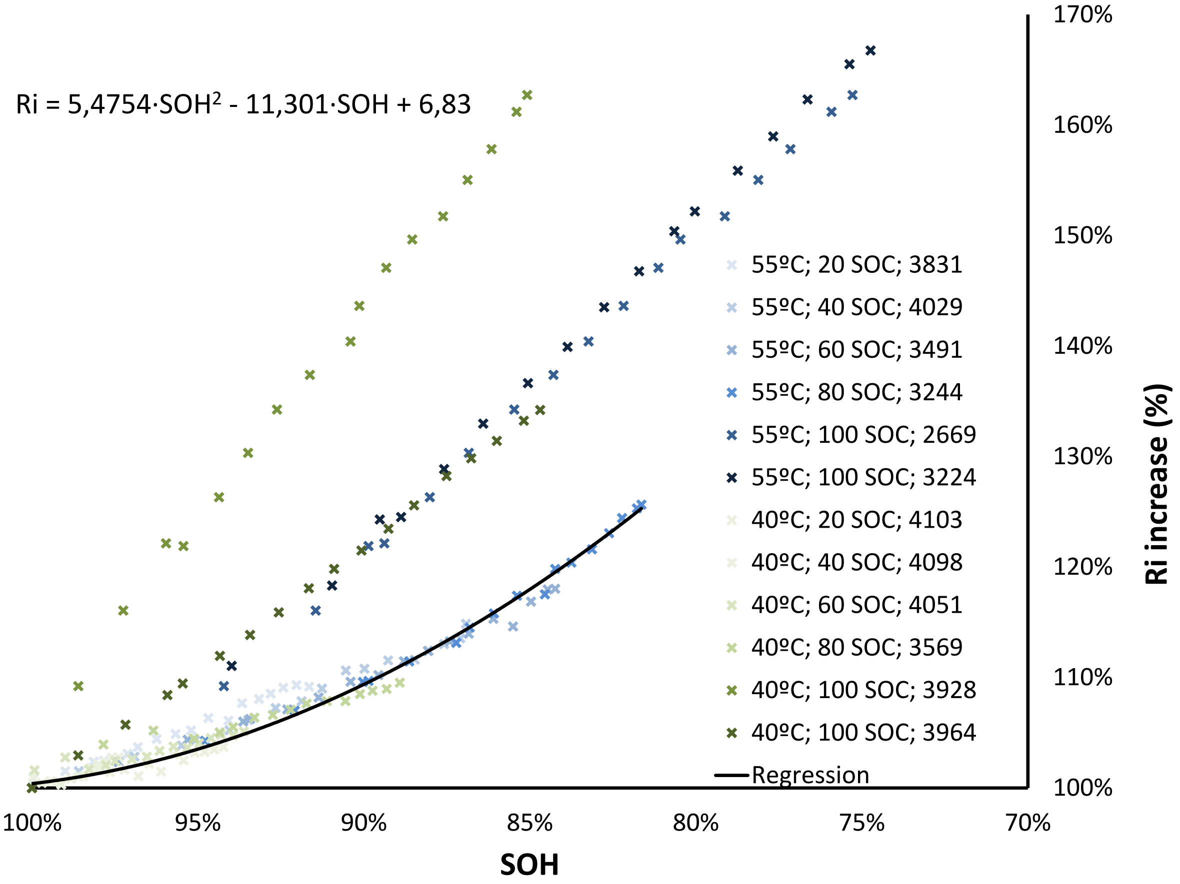


Figure 9.8: Polynomial relation between the internal resistance increase (%) and SOH.

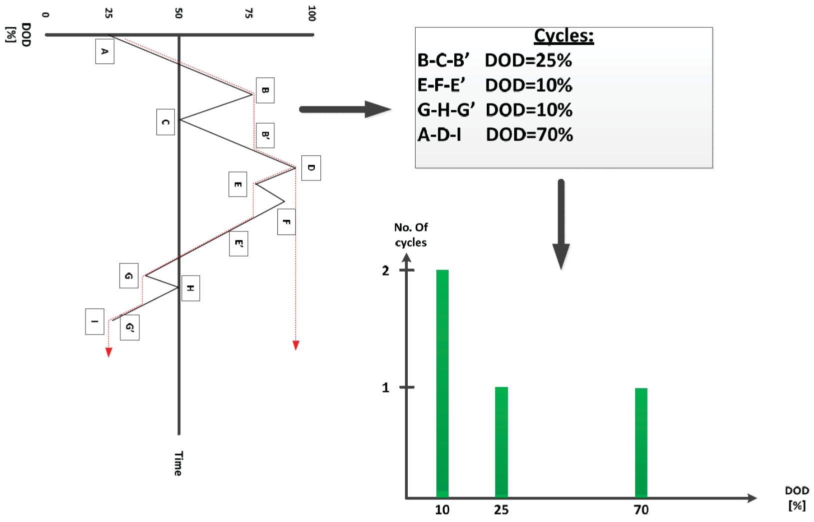


Figure 9.9: Example of a Rainflow Counting representing how one 70% DOD cycle may include two 10% DOD and one 25% DOD micro-cycle.
Source: Storage Systems based on Electrochemical Batteries for Grid Support Applications [63]

an exponential to a 2nd degree polynomial, increasing its impact as temperature gets further beyond 0°C. The Lithium platting effects occurring at low temperatures have not been deeply analyzed in the literature.

Anyway, it is assumed that the stationary batteries will not work under these low temperatures, so this handicap does not affect the RUL estimations obtained in this study.

Another useful limitation concerns the DOD interpretation. As it is prepared, it determines the biggest of the working DODs. That is, if the DOD gets bigger at each iteration (as it naturally happens by aging under simple cycles such as the ones from Chapter 8), the model takes it correctly under consideration. However, there are two aspects to improve. The first one is that, as it follows a logaritmic curve, a value of DOD below 1 makes negative effects. This would evolve into an improvement of SOH instead of a battery degradation, which is impossible. The second improvement to implement is the calculation of intermediate DODs. As it calculates only the bigger DODs, the intermediate DOD rinses are not considered. Which means that when the cycle follows an interrupted charge/discharge profile, this small micro-DODs are obviated and all the Ah throughput is affected by the aging impact of a bigger DOD. This occurs in some of the real cases that will be presented further in this chapter, such as the self-consumption using solar panels. Depending on the cycle this may cause an important RUL error.

The difficulty to calculate this small DODs is caused by the Rainflow Coulomb Counting described in the state of the art. It is impossible to determine the DOD prior to its ending, but the model calculates the aging effect at each instant. Thus, this value is unknown until the complete cycle finishes, as it is shown in Fig.9.9 .

Therefore, a DOD correction was included into this model after analyzing the input curves before its implementation. The Rainflow Counting is evaluated and the corresponding model DOD calculation is multiplied by a constant value, softening the impact per Ah throughput. This correction factor is not presented as it changes for every implemented curve.

In Chapter 8 it has been mentioned that the C-rate aging effect follows a 2nd degree polynomial expression [10]. For example, the model from Sarasketa et al. [125] was done to represent the aging of the cells under different aging circumstances. More exactly: Using C-rates at 1C, 2C and 3,5C and SOC at 5%, 10%, 60%, 100%. Its model responded quite well to the reference values. However, a deeper analysis of the 2nd degree polynomial expression exposed relevant limitations, as the C-rate aging factor is negative (improves SOH) below 0,5C and above 5C, which

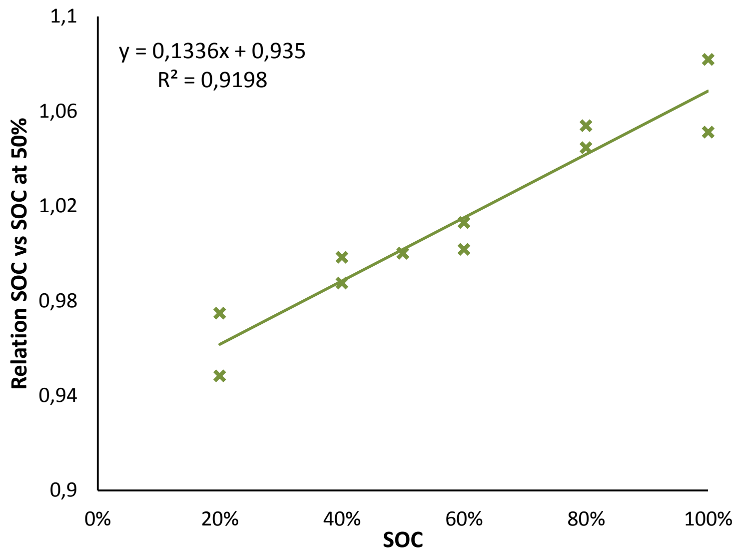


Figure 9.10: Relation between SOC and SOC at 50% at 55 and 45°C.

is an inherent contradiction. Mixing the concept from Sarasketa and the results presented by Dai et al. [127], the values θ_1, θ_2, θ_3 were calculated, being θ_1=0,00001, θ_2=0,0065 and θ_3=0,85.

Similarly, the effect of SOC is commonly defined by a linear equation [123], [36]. In this case, however, the effect of SOC was not extracted from literature, but from real testing results instead. Fig.9.10 represents the ratio values of SOC against SOC at 50% obtained from the calendar aging at constant temperatures (55°C and 45°C) and SOC (20%, 40%, 50%, 60%, 80%, 100% SOC). In Fig.9.10, the base case corresponds to the 50% SOC, while the effect of SOC on aging is compared to the aging at this percentage. That is, if a battery is stored at lower SOC, its degradation will be lower than this base case. On the contrary, if a battery is stored at higher SOC, its aging will be faster. The tendency line from Fig.9.10 defines how slower or faster this degradation is in relation to the 50% SOC base. In particular, a battery stored at a 20% SOC will age 0,96 times slower, while a battery stored at 100% SOC will aged 1,07 times faster. These values correspond to θ_4=0,1336, θ_5=0,935 in Fig.9.7 and in eq.8.5.

The last model limitation to take into consideration is the dispersion on aging. A battery is composed of many different cells packed together. Aging evolution varies on each cell due to its position in the battery pack, the facility to dissipate temperature or the inherent tolerances from fabrication among others. From the study entitled "The electric vehicle battery aging and how it is perceived by its driver" published by the DYNA journal [8], it was observed that although dispersion of EV batteries' cell aging was somehow camouflaged by battery unbalance, when they reached the 80% SOH the dispersion was below 3%. Fig.9.11 presents the voltage values against time on a 1C battery discharge. On the left, the maximal cell capacity dispersion of the analyzed EV at 82% SOH is shown. On the right, the 12 cell capacity test dispersion of two battery modules can be observed.

Assuming a linear tendency on cell aging dispersion, when they'd reach the EoL in 2nd life applications (60% SOH), the dispersion would be around 6%. Considering that the cell aging proposed is within the average, a ±3% deviation could be expected. As the presented model takes into account only one cell, unbalance is not foreseen, neither studied. Therefore, the expected RUL of a complete battery pack should contemplate a 3% deviation of the results presented.

Finally, a major assumption is taken for this model: the relations between the aging factors (eq.8.4, eq.8.5, eq.8.6 and eq.8.7) and the base Ah throughput aging evolution do not change much along time and they remain constant all along the simulation. Deeper studies should be done to validate this assumption.

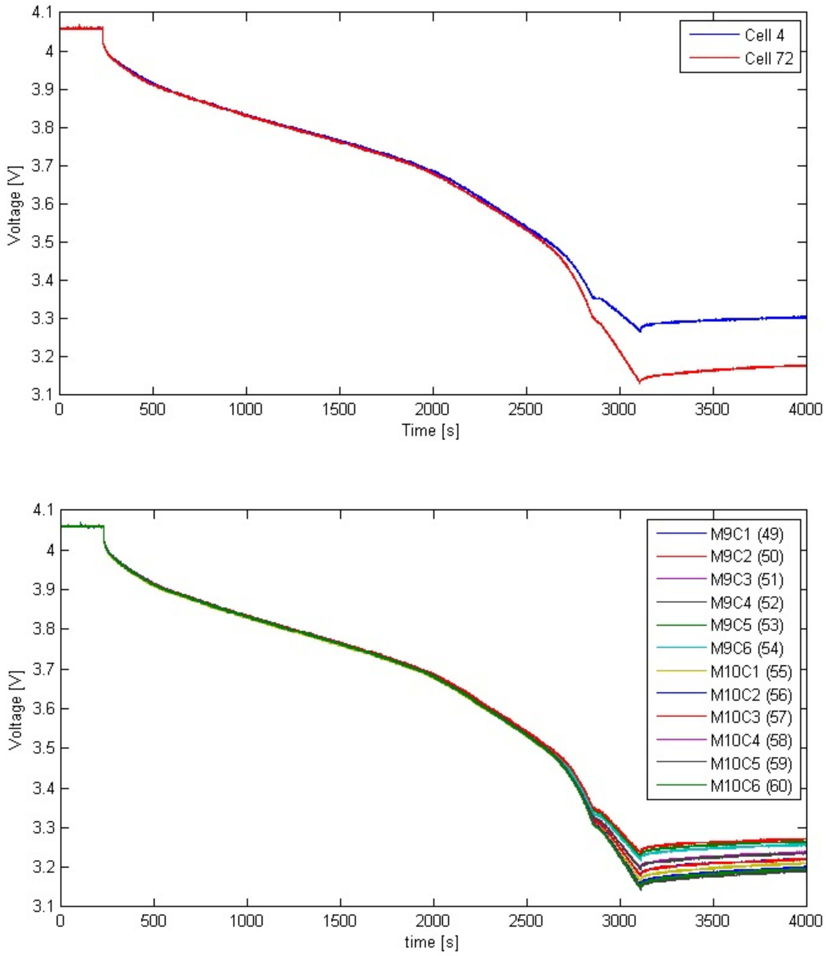


Figure 9.11: Cell capacity aging dispersion
Left: maximal cell capacity dispersion of the analyzed EV at 82%SOH (84 cells). Right: cell capacity test dispersion of two battery modules. Source: Canals Casals et al. [8]

9.5 Model evaluation for real case applications

Chapter 8 presented some battery 2nd life RUL resulting from simplified loads expected from stationary applications. In these cases, the charge/discharge cycles where done at constant current rates always following the same parameters. These are clearly not the real situations that batteries should face.

This section will present the model response under real load applications within the scope of the Sunbatt project.

The EPRI reports [16], [13] presented different applications where the energy storage systems could offer interesting services. In fact, they reported that the most economically interesting stationary applications where: the *Transmission* (TD) and *Time Of Use* (TOU) *Deferral* (being the investment deferral one of the major benefits) and the *Area Regulation*. The approaches done by Neubauer [47] and Cready et al. [43] confirmed that the previous economical estimations are consistent.

Additionally, the entrance of EVs in the automotive park incur into grid disturbances, specially when multiple fast charges are intended [71]. The use of batteries is suggested as a system to provide Peak Shaving and energy quality services during *Fast EV charges*.

Finally, knowing that the average home energy consumption is around 10 kWh and that the EV and PHEV battery packs have around 8 and 24 kWh energy capacity, the use of 2nd life EV batteries is considered ideal for residential self-consumption installations [12]

These 4 applications, schematically presented in Fig. 9.12, are the studied cases under the following specific configurations:

- Fast EV Charge (Fig.9.12 left): This particular case consists in an installation with 3 fast EV chargers and a grid connection of 70 kW power peak. Simulating the EV arrival and the fast charge curves it was calculated that, at some instants, 10 kW were additionally needed. This power increase is going to be offered by the car batteries instead of increasing the power supply connection and pay fixed extra tariff costs.

- Self-consumption (Fig.9.12 middle): This case consists in a house rooftop with solar panels. Its energy profile is used to calculate the energy storage needs: 8,8 kWh.

- Area regulation (Fig.9.12 middle): The Area regulation searches grid power stabilization. To be able to participate into the area regulation market, the battery owner should also be an electricity generator. The studied case is based on the same house used for the self-consumption application. Thus, the area regulation signal should be added to the self-consumption current profile. This load addition ends up with a higher amount of energy exchange (11 kWh).

- Transmission Deferral (Fig.9.12 right): This application should be understood to provide power support to a neighborhood grid transformer for few days a year, when the demand is higher than the average grid load and until an upgrade of the transformer is done. As the electricity consumption is supposed to increase in the following years, the quantity of days needing power support will increase gradually. A 20 year forecast was done obtaining a final amount of energy to store of 995 kWh.

For these simulations a constant temperature of 25ºC was considered eventhough it has been observed that the lifespan of batteries increases by 18% if the temperature follows an annual cycle from 10 to 30ºC.

The other input of the model is the current load that the battery should offer for each application. The intensity passing through the battery model will define the instant values of SOC, DOD and C-rates needed to calculate aging. The current intensity was calculated from each application's power and energy demand and the possibility to offer it with a determined number of batteries. For example, the Fast EV charge case needed 10 kW for short periods of time with a total daily energy exchange of 2 kWh, thus, 1 PHEV battery is more than enough to fulfil the requirements. The Self-consumption system needs to store more than the 6 kWh that our PHEV battery can afford at the beginning of its 2nd life. In this case, 2 PHEV batteries could be used. However, 2 PHEV batteries were not enough to afford the needs of the Area Regulation application, which is based on the self-consumption profile. Consequently, for both cases 1 EV (24 kWh) battery will be used. Finally, the huge amount of energy that the Transmission Deferral

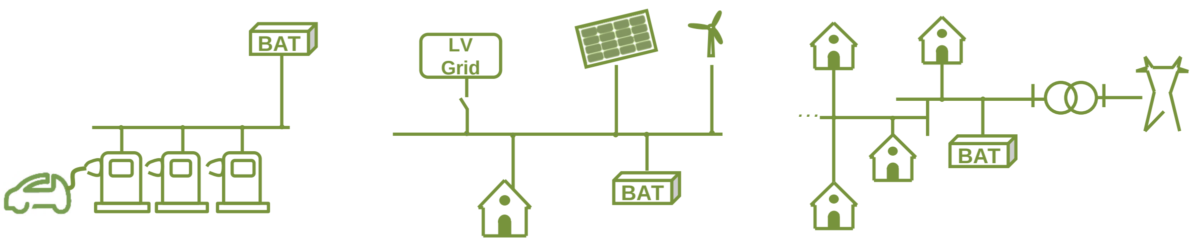


Figure 9.12: Schema of the four applications studied.
Left: Fast EV Charge; Middle: Self consumption and Area Regulation; Right: Transmission Deferral. Source: Canals et al. [92]

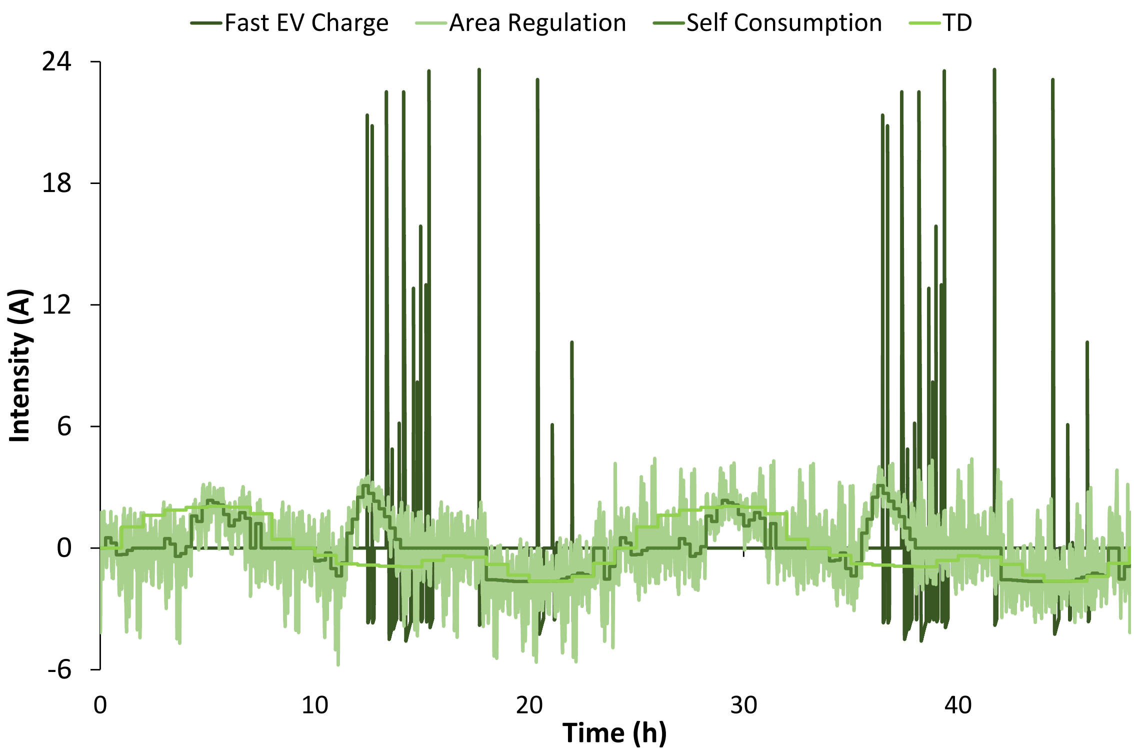


Figure 9.13: Current loads inputs for each application.
Source: Canals et al. [92]

needs during the last years imposes the use of more than 200 PHEV batteries. Fig.9.13 presents the current loads of each application. It can be appreciated that the Area Regulation (lighter green) current load oscillates around the self-consumption baseline (2nd darker green).

9.6 Results from real case applications

Like it was noticed in Chapter 8 after running the model, it can be observed that the battery lifespan can not be defined by a number of years, cycles or Ah throughput. In fact, it substantially changes according to each application.

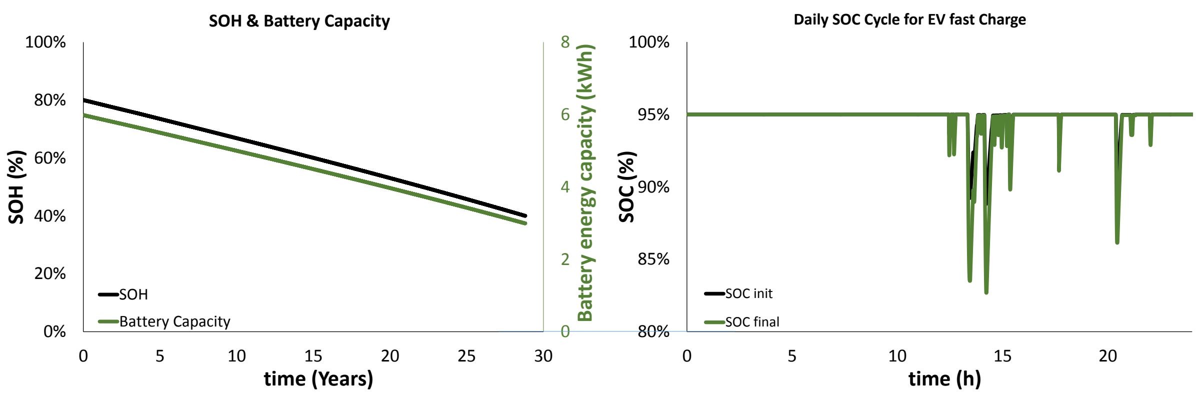


Figure 9.14: Fast EV charge results.
Left: SOH and Capacity fade along time. Right: Daily SOC cycle differences between the initial and end of the battery 2nd life. Source: Canals et al. [92]

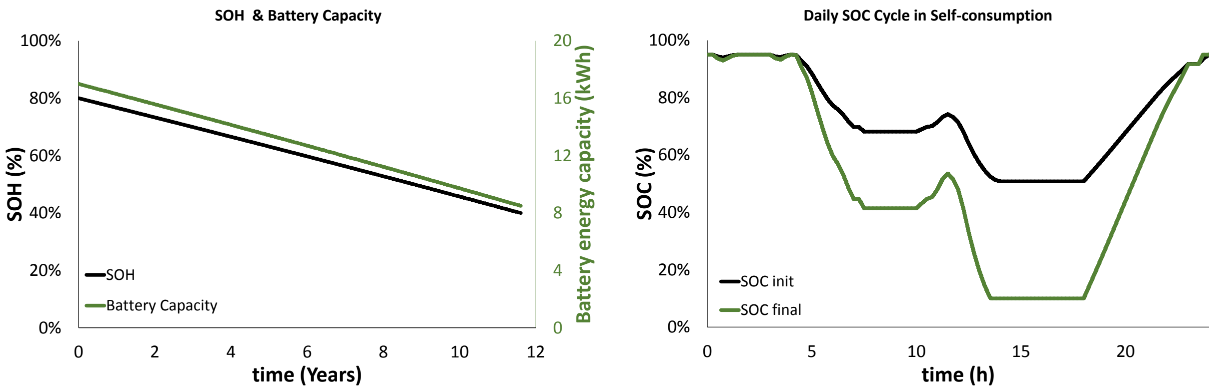


Figure 9.15: Self consumption results.
Left: SOH and Capacity fade along time. Right: Daily SOC cycle differences between the initial and end of the battery 2nd life. Source: Canals et al. [92]

Contrarily to the results shown in Chapter 8, the fast EV charge application is the one presenting a longer lifespan with almost 29 years of use, if the EoL is considered at 40% SOH. Although having almost the same name and concept, the fast EV charge on Chapter 8 considered a full charge done by the 2nd battery, while in this case, as explained in the section above, it uses the energy only for peak shaving demanding much less energy and power. This last results are presented in Fig.9.14. It should be noticed that, normally, the EoL of a battery is defined when it has lost a 20% of the initial capacity. Consequently, the normal EoL for 2nd life batteries should be defined at a 60% SOH. In this case, this corresponding RUL is 15 years. However, it can be seen (Fig.9.14 right) that the battery discharge is only around 15% SOC even when the EoL is reached. At this moment, reminding that the SOC range of the battery goes from 95% to 10% of the total capacity, the battery has still 70% of usable capacity, thus, a longer lifespan could be expected. For this reason the EoL is enlarged up to 40% SOH in this case. Although the system could still work under these conditions, the beginning of the battery sudden death, which is a sudden acceleration of the aging phenomena, is still not clearly defined. So, to ensure the presented results, the 40% SOH limit was taken.

Fig.9.15, shows the results of the SOH and capacity fade evolution along time for the self-consumption study case. An EoL of 40% SOH is established for the same reasons previously mentioned, achieving 11,6 years RUL. For an EoL at 60% SOH, 5,9 years of uninterrupted use should be expected. It can be appreciated that, at the EoL, the battery DOD achieves its maximum (85%), hence, if it works a bit more, it will start to have problems to follow the load demand and it will start to respond badly.

Comparing the results between the self-consumption (Fig.9.15) and the Area Regulation case (Fig.9.16), which share the same energy baseline, it can be appreciated that, when including the Area Regulation services into the self-consumption, the aging is substantially accelerated and the RUL decreases near the 50%, reaching only 5,7 years. However, the EoL (85% DOD) is reached, in this case, at 55,7% SOH, much before the 40% SOH of the previous cases. This difference is basically explained by the SOC curve (Fig.9.16 right). If the system should work beyond this 55,7% SOH limit, the battery would miss some of the requirements in deep discharges and, thus, it will respond incorrectly. Moreover, if this result is compared to the standard 60% SOH, the obtained RUL is 4,7 years, which is an 80% lower than the 5,9 years obtained in the self-consumption case. Additionally, the ripples caused by the current variability from the Area Regulation are observable in Fig.9.16 right, having a 48 hour cycle instead of a daily cycle.

Lastly, the results from the Transmission Deferral study case are presented in Fig.9.17. This case is particularly different to the others because the frequency of use increases every year, thus, in the first year there are less than 20 cycles and during the 20th year the battery works almost

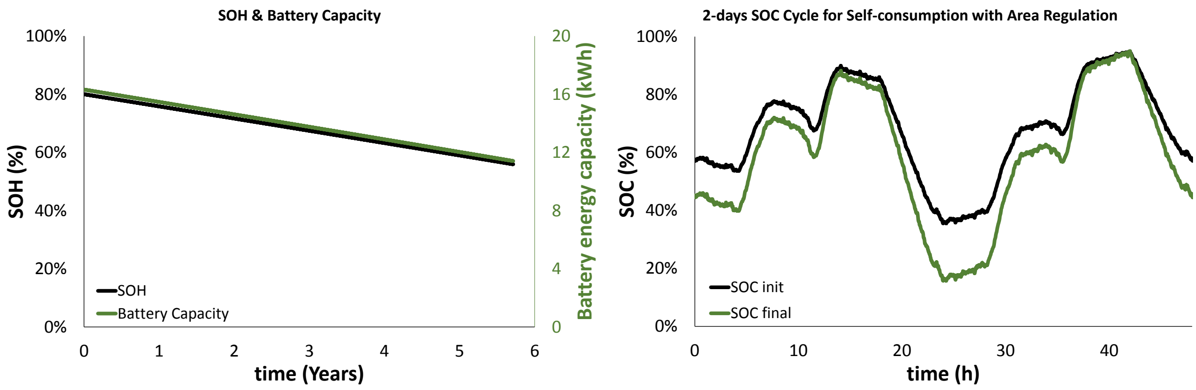


Figure 9.16: Area Regulation results.
Left: SOH and Capacity fade along time. Right: Daily SOC cycle differences between the initial and end of the battery 2nd life. Source: Canals et al. [92]

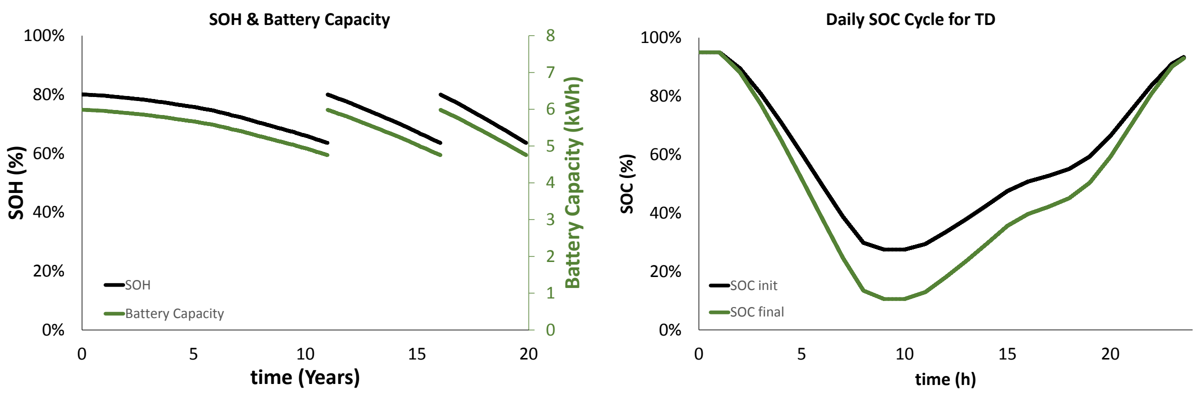


Figure 9.17: Transmission Defferral results.
Left: SOH and Capacity fade along time. Right: Daily SOC cycle differences between the initial and end of the battery 2nd life. Source: Canals et al. [92]

all days. To reach the 20 years forecast for the TD application, the results from Fig.9.17 left show that two battery sets replacements should be done during this period. The first pack of batteries will last almost 11 years, while the RUL of the following set of batteries is 5 and 3,8 years respectively. Again, at the EoL, the batteries use their entire 85% DOD (Fig.9.17 right).

It has been mentioned in this and in the previous chapter, that battery aging occurs either while cycling or during storage. The ratio of the cycling aging effect on the overall aging along time is observable in Fig.9.18. Consequently, the effect of calendar aging is the subtraction of the cycling aging to the unit, or the remainder. The cycling effect finishes above the 80% of the total, meaning that it has a higher impact on aging than storage. Additionally, it should be noticed that the cycling aging effect increases along time. This is is explained by two reasons: In the first place, the DOD load cycle increases while the battery ages and its impact increases accordingly. In the second place, as the calendar aging follows the *Arrhenius*-like curve, its impact decreases with time. Thus, if the energy exchange load has low demand, a 2nd life battery could last longer than a new one with the same capacity when installed on a stationary application.

It should be mentioned that the fluctuation of the cycling effect weight during the first years of the first battery from the Transmission Deferral study case (TD 1 in Fig.9.18) is mostly caused by the randomly distributed cycles. During the first year, the battery is only activated 17 days and in the second 34. Afterwards, as the cycles are more and more frequent, this fluctuation is reduced and the cycling effect increases substantially.

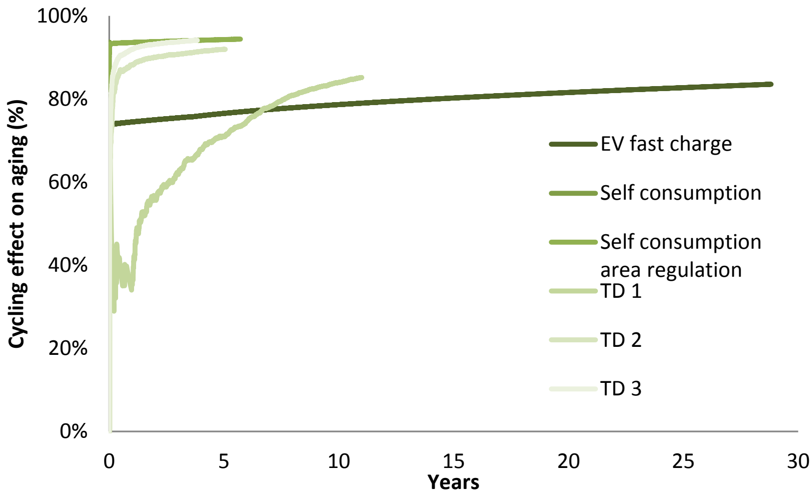


Figure 9.18: Weight of the cycling aging effect on the overall aging of the battery for each application.

These results will permit an economical approach and will help the decision to invest or not in each application. In parallel, Life Cycle Analysis, such as the ones in Chapter 11 and 12 can be executed taking these results for the calculations.

9.7 Conclusions from real case applications

. The 2^{nd} life of EV batteries follows two of the three "R" expected from an environmental point of view: Reuse and Reduce.

- Reuse because it uses batteries that, otherwise, would be considered a waste and would be sent to recycle.
- Reduce because the use of 2^{nd} life batteries eliminates the need of fabricating new batteries for the studied applications.

The last "R", from recycle, is already being implemented. However, the battery reuse postpones it and gives time to the recycling industry to develop better and more efficient methods.

2^{nd} life EV batteries may be used to provide power support on fast EV charge stations. These batteries would last over 30 years and enhances the electro-mobility by offering solutions to the fast charge.

The other clean energy application studied is the self-consumption application with solar energy generation. In this case, the battery RUL is close to 12 years and offers reliability to the renewable electricity generation, solving one of their major drawbacks and enhancing its entrance into the market.

The other two applications studied, Area Regulation and Transmission Deferral, are services from a grid oriented approach. However, the re-use of batteries is a cleaner alternative that is estimated to last almost 6 and 12 years respectively.

Chapter 10

Aging Model Validation

"Quand il y a des gens qui font tant de découvertes pour être utiles, faut-il que d'autres se donnent tant de mal pour être nuisibles!".

Guy de Maupassant "*Boule de suif*".

10.1 Motivation

The aging model and some simulation's results have been presented in chapters 8 and 9 showing interesting opportunities to enlarge the EV batteries' lifespan. However, these results would not be representative without a validation of the model.

This chapter presents the validation of the aging model in order to strengthen the relevance of the expected RUL obtained for 2^{nd} life applications. This chapter will demonstrate that, although not perfect, the model results are close to what they should be expected and its use is recommended for cost effective RUL approximations.

This chapter has been published in no journal neither in conferences due to the confidentiality of the presented values and results. Confidentiality and diffusion of research results might sometimes be in conflict, which occurs too frequently when the research field is funded by private companies.

The model is validated following two different approaches.

The first approach is based on the use of the battery during its 1^{st} life. That is, under EV conditions. The validation will be obtained relating the mileage of the EV when it reaches the 80% and 70% SOH against the 100.000 and 150.000 km warranty offered by car manufacturers.

The second approach is much more experimental and has more detailed and reliable results. It is based on the SOH values obtained from laboratory testing. 36 cells were aged following different current profiles under controlled temperature. Then, the cell aging will be compared to

Chapter 11

Environmental Impact of the Electric Vehicle

The headlines are very eloquent: "Thousands of millions wasted in the UN climate program". "The truth about Kyoto: Wealthy gains and low emissions saving". "Confusion rules in the initiative of the UN to fight emissions". "The political solution to fight global warming does not work". "The dramatic failure of the UE directives to fight climate change". "The fraud of the carbon trade: Why do we pay the 3rd world to contaminate its environment?".

Tomra Gilbertson & Oscar Reyes *"Carbon trade. How it works and why it fails"*.

11.1 Motivation

Business is business. Then, why on earth should there be two chapters in a business modeling thesis regarding the environmental profits or burdens of the product?

The answer to this question is found in the origin of the business idea. The battery re-use, although environmentally interesting, comes from an economic perspective. This same situation is found in the apparition of the electric vehicle. Every car should successfully pass the emissions' legislation of the country where it is sold. Legislation become more and more restrictive with each revision, as shown in Fig.11.1 where the evolution of the European directives regarding different gas emissions on traction vehicles is presented.

Unfortunately (or not), the internal combustion engines achieved a point in which huge investments offer small reductions on emissions and are reaching an horizontal asymptote. To continue in the business, car manufacturers are incorporating different techniques to reduce the emissions, such as the AdBlue, regarding the NO_x on diesel vehicles, while others followed less fortunate strategies.

Nevertheless, in the end, car manufacturers are all comprehending that, in order to accomplish the EU Euro-6 and other international environmental directives, their fleet should be electrified.

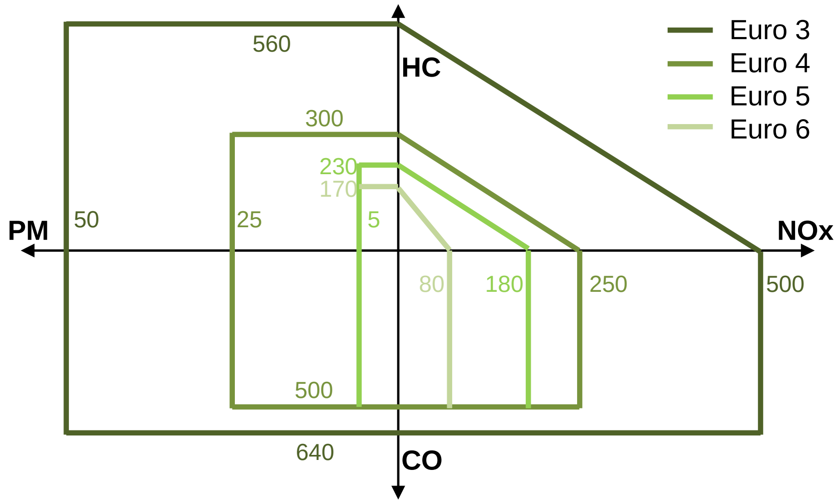


Figure 11.1: Evolution of the European directives on emissions on traction vehicles. Source: Volkswagen AG.

This is one of the reasons that transformed the EV into an expensive but interesting sweet and all car manufacturers are selling or designing new PHEV and EV models. Fig.11.2 presents the technology deployment to face the reduction on CO_2 emissions in transportation.

So, finally, it is on behalf of environmental restrictions that the EV business arise. Still, regulations and legislation concentrate their attention in particular effects. Until now, transportation was tied to tailpipe emissions and, consequently, the administration focused on that to write down directives and laws. The EV, having no tailpipe emissions, is out of the scope and satisfactorily passes all these restrictions.

But does this means that the EV is indisputably beneficial for the environment? The answer is: obviously NOT.

In order to effectively understand the environmental kindness or burdens of EVs a complete

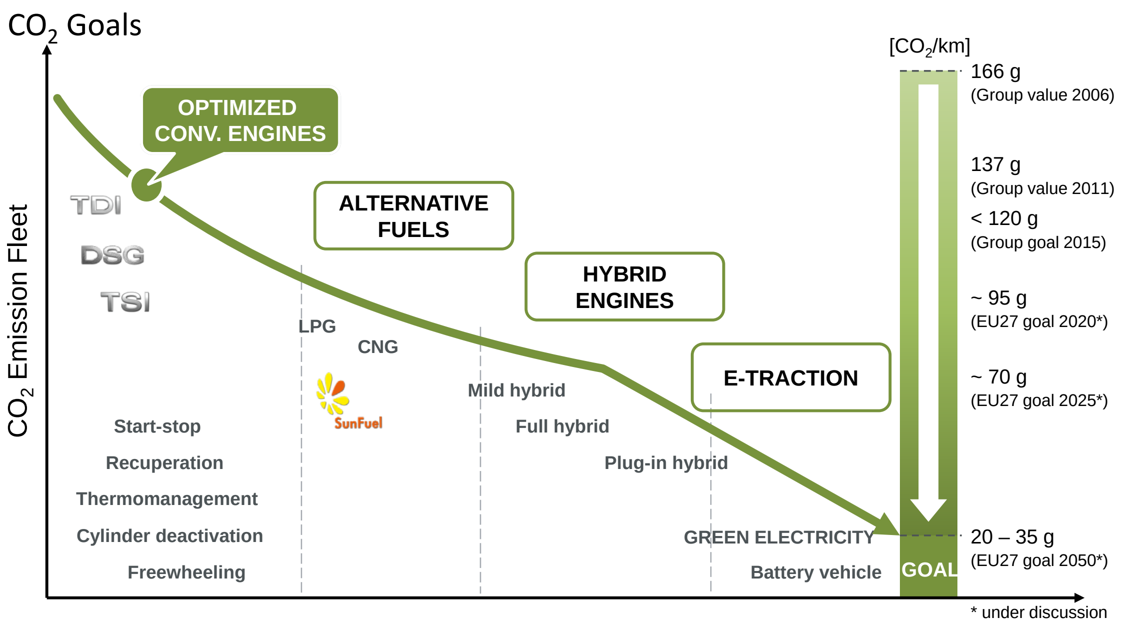


Figure 11.2: Technology deployment for emission's reduction. Source: SEAT.

Life Cycle Assessment (LCA) should be carried out. As this thesis is focused on the 2[nd] life of EV batteries and transportation's impact has been generally related to CO_2, the environmental study executed in the following chapters corresponds to a Life Cycle Carbon Dioxide Assessment (LCCO2). This LCCO2 should incorporate the study of both: the 1[st] and the 2[nd] life.

This LCCO2 study is then divided in two chapters: Chapter 11 will delve into the EV impacts, or 1[st] life, while the complete LCCO2 will be studied in Chapter 12, as there are many alternatives for 2[nd] life of batteries and each one have different impacts.

Chapter 11 is based on the article *Do e-mobility and energy policies match in Europe? Analysis of environmental benefits from electric vehicle use*, under review in the Journal of Cleaner Production. This paper was written with the participation of the IKERLAN research center, who analyzed the different consumption of EVs under various driving cycles.

Then, Chapter 12 completes the LCCO2 of EV batteries incorporating the 2[nd] life. The results will be compared to the theoretical optimistic conclusions from chapter 10 with tangible values.

Additionally, chapter 12 compares the material properties used in EV batteries, noticing that battery and car manufacturers prefer to use materials providing better properties in power and energy density above lifespan.

Chapter 12 is based on the article *2[nd] life of electric vehicle batteries: relation between materials degradation and environmental impact* published in the International Journal of Life Cycle Assessment (ISSN 0948-3349) in collaboration with the CIC-Energigune research center. It was published on June 11[th] within the Electric Vehicle Special Issue. DOI: 10.1007/s11367-015-0918-3.

It should be noticed that this article was written before having finished the Matlab model described in this thesis. Thus, the battery RUL was calculated with an earlier equation. However, the sources and roots are similar and the results, although slightly different, should be considered as a first RUL approach that have no significant impact on the conclusions.

11.2 Introduction

During the last century, the automotive industry and the electric energy generation sector revolutionized the society, bringing motorized mobility to the layman and powering up their homes. However, nowadays both transportation and energy generation sectors are key actors in the GHG emissions scene, gathering about 13% and 15% of the total GHG emissions worldwide, respectively [1].

European directives concerning the transportation emissions (from Euro 1 to Euro 6) [1] [132] have pushed automaker companies to continuously improve their ICEV. However, ICEVs seem to be reaching their techno-economical limits, pushing forward alternative mobility solutions, powered by less pollutant energy sources. Among those solutions, the EV powered by Li-Ion batteries is probably the most popular [3], whose penetration in the automotive market is steadily increasing in the last years [117], as shown in Fig.11.3.

The EV has null tailpipe emissions, which helps fighting localized pollution, an especially important fact in urban concentrations. Nevertheless, this does not mean that the EVs have no environmental burdens at all [2]. Although having some hints on how to improve the sustainability in the EV manufacturing supply chain [133], the manufacturing of an EV still entails higher environmental impact than that of an ICEV, being battery production one of the main contributors to the production phase GHG emissions [134], [135]. Similarly, electricity consumed during the use phase for charging the EV mostly comes from the existing electricity grid, and being the energy generation sector one of the most pollutant sectors worldwide, this also supposes an implicit carbon footprint that cannot be neglected.

[1] https://www.dieselnet.com/standards/eu/ld.php. Accessed the 09052015

In this way, analyzing the environmental burden of EVs entails studying the different energy consumption phases involved in the vehicle lifetime. The Well-to-Wheel (WTW) life cycle methodology is commonly adopted to estimate the environmental impact of common ICEVs, [136], [137]. It typically consists of two steps: (i) the Well-to-Tank (WTT) environmental impact calculation, which considers the impacts from fuel extraction, refining and distribution to fill the vehicle tank, and (ii) the Tank-to-Wheel (TTW) impact calculation, which analyzes the impact produced in the fuel combustion to generate traction power and energy. The ICEV impact is most dependent on the TTW phase (or use phase), being the WTT a globalized factor.

In the case of EVs, the environmental impact assessment is calculated following the same WTW methodology. Nevertheless, being null the tailpipe emissions of such vehicles, the electricity generation process has a significant influence on the final EV environmental impact results [138]. Divergent results have been reported in literature when evaluating the TTW phase, showing a wide range of energy consumption values going from 0,10 kWh/km to 0,24 kWh/km, [136], [109], [137], [139], [140]. Moreover, it has to be pointed out that the consumption on EVs does not only depend on the technology, but also on driving habits, the use of auxiliaries (such as air conditioning and heating system, defroster, power brakes, radio...) and the weather conditions [106], [109]. In addition to this large consumption variability, the emissions created from electricity generation and distribution to charge the EVs (WTT), have also been studied to determine the Global Warming Potential (GWP) of these vehicles[139].

The whole assembly of these two steps (WTW life cycle) provides the environmental impact results for a single vehicle and it shows that, unlike the ICEV, it may substantially change depending on the electric energy source and the EV consumption in the use phase [136]. The review written by Hawkins et al [137] covering several studies aboutLCA of EVs, showed that most of these studies include the fuel and electricity generation in their calculations, and that the GWP is the most widespread parameter to evaluate the environmental impact. However, usually the impacts of different fuel sources are calculated and then compared with the electricity generation mix of a specific country. Some studies compare different driving cycles between EV or against one ICEV [141], but none does a complete comparison of related cycles. Therefore, there is no clear understanding on when or where an EV is worth to be used.

This chapter focuses on the calculation of the maximum emissions of the energy generation phase that can be permitted in order to keep the EV environmentally profitable against ICEV. For this to be done, first the electricity energy generation systems of many European countries

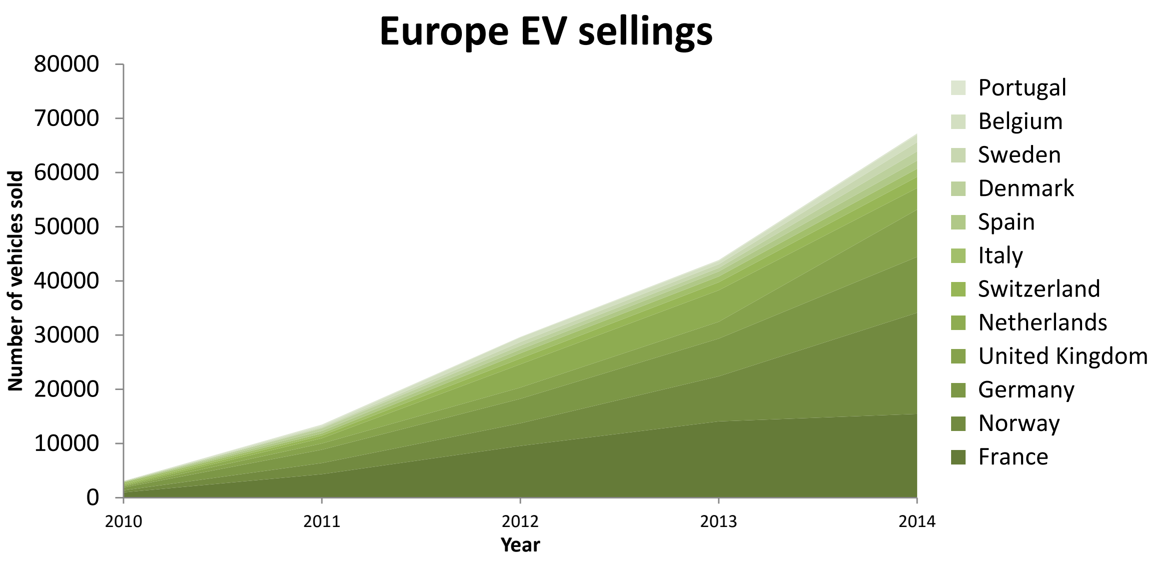


Figure 11.3: EVs sold in European countries during the period 2010 - 2014.

are analyzed, taking into account their different energy strategies, different electricity mix, and thus, different GHG emissions produced during the energy generation phase [142], [143]; [139], [144].

Further, an analysis of the effect of the driving pattern upon the efficiency of the EV, in the use phase, is carried out. Knowing that the use phase leads to high variability in the final environmental impact result [2], the energy consumption is evaluated under various EV standard driving profiles. Then, this analysis is extended for a range of auxiliaries' consumption conditions, offering a deeper view of their effect upon the vehicle efficiency.

Finally, the impacts calculated in the energy generation phase and during the use phase are cross checked, with the objective of evaluating the coupled impact between energy generation emissions and energy use efficiency. Studies in literature showed that EV incentives have a positive response in the automotive market share [145]. Hence, the results obtained in this paper are used to further conclude, depending on their current energy generation infrastructure, in which European countries it makes more sense to boost the use of electric vehicles, if it corresponds to its reality and to determine if there are incoherent strategies between the electricity and transportation environmental policies.

11.3 Methodology

The methodology followed for the calculation of the GHG emissions associated to EV and ICEV is described in this section, which is divided into different parts: the energy generation phase, use phase and total emissions comparison between ICEV and EVs.

Energy generation phase:

A deep WTT analysis takes into account many steps from the extraction of energy source material to the electricity power distribution [146], [147]. For this to be done, this study takes advantage of the information about the electricity generation mix in many European Countries, available in Eurostat databases from 2013 and the FP7 funded project LCA2GO [148]. These databases consider generation, transportation and distribution emissions from the power plant to the home plug. Then, the emissions analysis in the energy generation phase is completed by including the environmental impact of raw power sources acquisition and the efficiency of the EV charger according to equation 11.1.

$$GWP_i = \frac{MIX_i \cdot (1,22 \cdot \alpha_{NG_i} + 1,05 \cdot \alpha_{C_i} + 1,02 \cdot \alpha_{P_i})}{\eta_{char}} \tag{11.1}$$

Where i represents the country, α corresponds to the share of Natural Gas (NG_i), Coal (C_i) or Petrol derivate (P_i) used to electrify the country and the η_{char} is the charger efficiency, fixed at 0,9.

Energy use phase:

Once the energy generation phase emissions per kWh are calculated, it is necessary to find out the kWh needed to run a certain amount of km, i.e. to calculate the efficiency of a particular EV. The TTW efficiency represents how the energy charged to the vehicle is transformed into movement, which entails an important effect over the final WTW emissions.

It is important to evaluate the use phase (or TTW efficiency) under different scenarios to notice how relevant the emissions per country are when taking into account the total WTW emissions, which depend on boundary constraints such as the climate conditions, the speed limits or the driving habits on each country.

For the evaluation of the TTW efficiency, an approach similar to that reported by Peterson et al. has been followed [67]. In this way, the power consumption for a certain driving cycle can be calculated according to the following equations eq.11.2 if $a<0$ and eq.11.3 if $ac>0$:

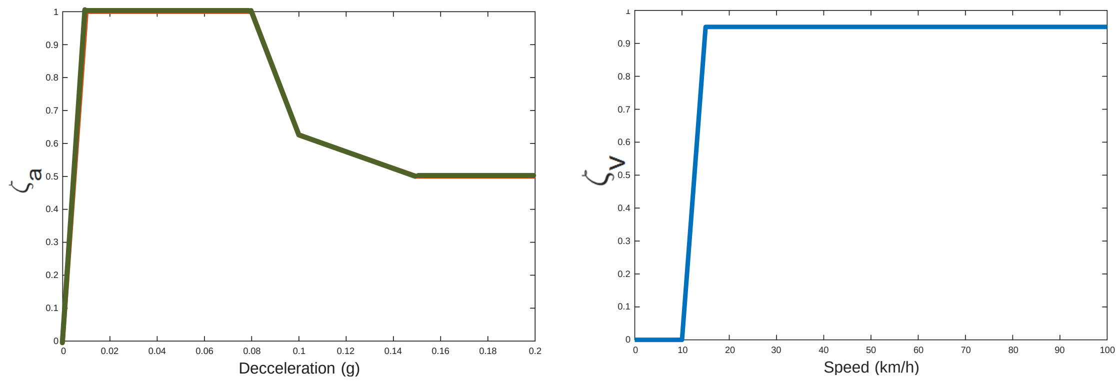


Figure 11.4: Regenerative braking efficiency in function of vehicle speed (right) and deceleration force (left).

$$P = [(m \cdot a + \frac{1}{2} \cdot \rho \cdot \nu^2 \cdot C_d \cdot A + C_{rr} \cdot m \cdot g) \cdot \zeta_\nu \cdot \zeta_\alpha] \cdot \eta_{Pt} \cdot \nu + P_{aux} \tag{11.2}$$

$$P = \frac{m \cdot a + \frac{1}{2} \cdot \rho \cdot \nu^2 \cdot C_d \cdot A + C_{rr} \cdot m \cdot g) \cdot \nu}{\eta_{Pt}} + P_{aux} \tag{11.3}$$

Where a and ν are the acceleration and the speed of the vehicle, respectively; A,C_d,m and C_{rr} are the frontal area of the car, the drag coefficient, the mass of the vehicle and the rolling resistance, respectively; g is the gravitational acceleration and ρ is the density of the air.

In addition, it is assumed that when negative accelerations are registered, the regenerative braking contributes to recharging the batteries, thus reducing the total energy consumption on a certain trip. However, the energy recovered during the regenerative braking depends on the instantaneous speed and acceleration of the vehicle [149], [150], [151], [152], [153]. For this purpose, the coefficients ζ_v and ζ_a have been included in eq.11.2 and eq.11.3 according to Fig.11.4, as implemented in [152]. These two coefficients represent the percentage of the total regenerative force that can be recovered depending on the vehicle speed and the deceleration of the vehicle, respectively.

Similarly, the total powertrain efficiency, η_{Pt}, is calculated in eq.11.4 as the multiplication of the efficiency of the various parts connected in the powertrain of a battery EV, described as follows according to [136], [109], [149], [154], [155].

$$\eta_{Pt} = \eta_{Batt} \cdot \eta_{inv} \cdot \eta_m \cdot \eta_{tr} \tag{11.4}$$

Where η_{Batt}, η_{inv}, η_m, and η_{tr} are the efficiencies of the battery pack, the inverter, the electric motor and the transmission system (transmission shaft, gear, differential, etc.), respectively.

Finally, the variable P_{aux} in eq.11.2 and eq.11.3 represents the power consumed by the auxiliaries in the EV, including air conditioning, cooling and heating system, radio, light or any other accessories. In this case, a standard auxiliaries' consumption of 800 W has been assumed, which may vary between 500 W and 3.500 W according to consumption ranges widely described in literature [156], [76], [157], [67], [158]. The average auxiliaries' consumption per country has also been calculated taking into account the maximum and minimum average temperatures and using the relation from [76] of auxiliaries' consumption depending on the difference between the external and internal car temperature.

Several standard driving cycles have been used to extend the evaluation of the TTW efficiency. Although it has been reported in literature that standard driving profiles do not usually represent the real EV performance [159], [160], [161], it is assumed that the aggregation of the results obtained with various profiles would enhance the representativeness of the analysis in a cost-effective way. Therefore, six standard driving profiles have been considered, covering a wide range of driving scenarios. Thereby, both the New European Driving Cycle (NEDC) and the Worldwide harmonized Light duty driving Test Cycle (WLTC) have been selected as baseline cycles to evaluate the EV performance [160]. NEDC is the standard driving cycle used in Europe for the environmental impact evaluation and range quotation. However, WLTC is the standard driving cycle called to substitute the NEDC, which prevails over other standard cycles for the performance assessment of EVs on the EU in the near future. Additionally, the Supplemental Federal Test Procedure (US06) and the Highway Fuel Economy Test Cycle (HWFET) American standards have also been included in the analysis, as representatives of different kinds of highway driving patterns. Finally, the Urban Dynamometer Driving Schedule (UDDS) and the New York City Cycle (NYCC) have been also included to analyze the effect of urban driving patterns and stop-and-go driving conditions over the energy consumption of an EV.

Total emissions calculation and comparison:
The total emissions calculation analysis is the bond of energy generation and energy use phase analysis, which in this case is focused on the GWP of EVs in many European countries, measured in kg of CO_2 e. Moreover, the analysis permits finding out the energy mix for which EV and ICEV emissions equalize, and thus evaluating the convenience or not of EV use enhancement in function of the energy generation infrastructure.

Following eq.11.5, the GWP of a single EV is calculated per country. Considering the electricity mix calculated in the energy generation phase, multiplying it by the distance (D) covered by the EV and the energy consumption (E) of the EV per kilometer, the GWP of an EV related to its whole-life use phase is calculated. Moreover, as mentioned in the introduction section, the EV fabrication entails higher environmental impact than the fabrication of ICEV. This fabrication impact is stated in the literature to be c.a. 11.000 $kgCO_2e$. [142], [143], [139]; [162], which is added for the calculation of the total GWP. Being the EV impact calculated on a yearly basis, it has been considered an average of 12.000 km (D) and the EV fabrication impact is divided by the expected EV lifetime (GWP_{fabEV}), which is considered to be 8 years according to the warranty offered by car manufacturers. This timeframe might seem short compared to other studies, that normally go from 100.000 to 300.000 km [137], but considering that the average age of ICEVs in the analyzed European countries is around 6-8 years (Eurostat) and that EVs use a new technology, a conservative value was preferred.

$$GWP = MIX \cdot E \cdot D + GWP_{fabEV} \tag{11.5}$$

This value, multiplied by the number of cars sold in each country, shows the whole environmental impact of EVs and allows comparing their effect in several European Countries.

The same approach used to obtain the GWP of the EV is used to calculate ICEV impact by means of eq.11.6. In this case, the FSEM project assumed that the GWP of the fabrication phase of ICEVs is 6.500 $kgCO_2e$., almost the half of an EV [143]. The GWP_{km} depends on the driving cycle studied. The base case, using NEDC, is extracted from [141] and all the other emissions per kilometer are extracted from literature and related to the NEDC [163], [164] and [160] for the WLTC.

$$GWP_{ICEV} = D \cdot GWP_{km} \cdot + GWP_{fabICEV} \tag{11.6}$$

Eq.11.6 does not depend on any specific country characteristic. It is herein used as the baseline to observe the convenience or not of EV market enhancement around Europe. If the calculated

EV impact (for each of the driving cycles and for the whole range of auxiliaries' consumption values) is lower than this baseline, it means that the use of EV supposes an environmental benefit. On the contrary, if the calculated EV impact is higher or equal to the baseline ICEV impact, it would imply no benefits by the use of EV.

Once the EV consumptions are obtained for the different driving scenarios, by equalizing eq.11.5 and eq.11.6, and isolating the mix variable, the electricity mix emissions value for which the emissions produced by an EV equal the emissions produced by an ICE vehicle can be calculated according to eq.11.7).

$$MIX = \frac{D \cdot GWP_{km} + GWP_{fabICEV} - GWP_{fabEV}}{E \cdot D} \tag{11.7}$$

Note that eq.11.7 represents the threshold values from where the EV use provides environmental benefits for the different driving conditions included in the analysis. This value can be easily compared to the current energy generation mix of each country, to assess the convenience of EV use from an environmental point of view.

11.4 Results

The main results obtained in the different energy generation phases are described in the lines below, along with the most representative results obtained when comparing ICEV and EV emissions.

Energy generation phase:

The GWP per kWh of electricity used when charging an EV is shown in Fig.11.5 for the European countries that sold more EVs during this last decade. This figure summarizes the results of the WTT phase, showing the wide range of emission values per country calculated from eq.11.1. The results depend on the electricity generation infrastructure and the costs associated to power source acquisition, transportation and transformation.

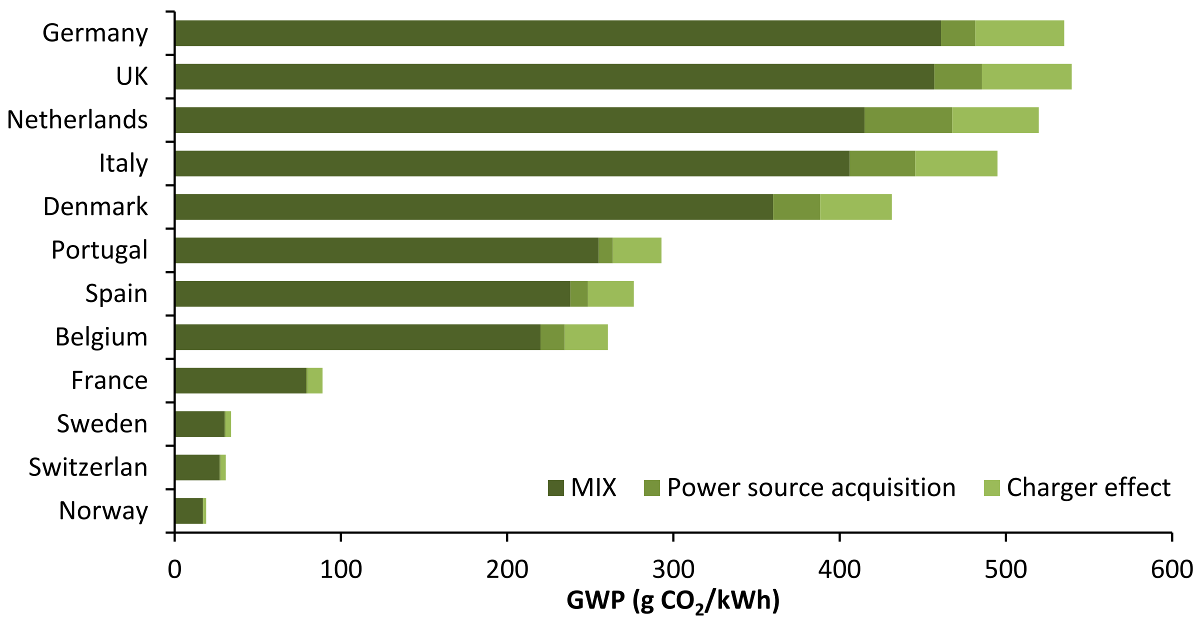


Figure 11.5: Emissions of EV charging from electricity grid energy per country considering the fuel acquisition and charger's efficiency.

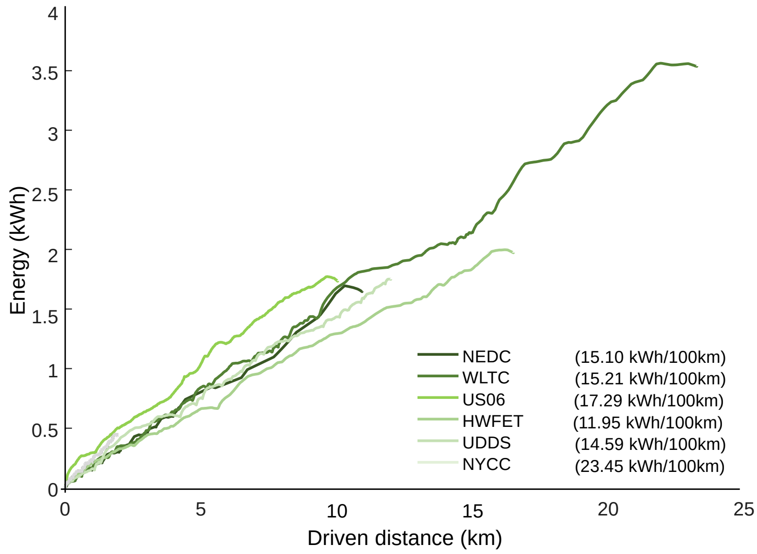


Figure 11.6: Energy consumption versus driven distance for a constant auxiliaries' consumption value of 800 W.

These results show large differences in CO_2 e. emissions between the different countries in Europe, ranging from 19 $gCO_2e.$ in Norway up to 534 $gCO_2e.$ in United Kingdom.

Energy use phase:

With the objective of extending the WTT analysis, the TTW efficiency and energy consumption of an EV has been analyzed under a wide range of conditions, as previously mentioned in the methodology section. A typical hatchback electric vehicle has been considered in the analysis for the evaluation of the EV performance. The main vehicle characteristics and the rest of the relevant variables included in the analysis, eq.11.2 and eq.11.3, are shown in Table.11.1.

The EV performance analysis shows, for a constant auxiliaries' consumption of 800 W, henceforth considered the standard auxiliaries' consumption value, a wide range of energy consumption values depending on the driving profile considered, as it can be seen in Fig.11.6.

Similarly to the ICEV, the EV also finds its optimal efficiency range in speed values from 20 km/h to 80 km/h [156], [157]. Although the energy regeneration capability improves the EV efficiency under non-constant speed, the implemented regenerative braking strategy limits the maximum energy recuperation to certain speed and acceleration range, Fig.11.4. Those issues result in EV optimal performance in suburban areas, as shown in Fig.11.6.

It should also be noted that in urban areas, where the vehicle speed is lower, a greater time is needed to cover the same distance, which also aggravates the effect of auxiliaries' consumption. For this effect to be analyzed, the effect of the auxiliaries' consumption has been evaluated, ex-

Table 11.1: Main characteristics considered for modeling the EV and relevant physical variables

Characteristic	**Variable**	**Value**
Frontal area of the vehicle [m]	A	2.28
Drag coefficient	C_d	0.27
Rolling resistance	C_{rr}	0.01
Vehicle mass [kg]	m	1401.59
Air density [kg/m3]	ρ	1.225
Gravitational acceleration [m/s2]	g	9.8

Table 11.2: TTW EV consumption (in kWh/100km) under different driving cycles and with different auxiliaries' consumption values

Cycle	Type	Auxiliariesm Consumption			Variation vs. WLTC (800 W)
		500 W	800 W	3.500 W	
NEDC	Urban + Extra-urban	12,91	13,81	21,94	96%
WLTC	Urban + Extra-urban	13,61	14,25	20,05	100%
US06	Highway	18,34	18,72	22,17	131%
HWFET	Extra-urban	11,15	11,53	15,01	81%
NYCC	Urban	20,09	22,71	46,34	159%
UDDS	Urban	12,75	13,70	22,26	96%

tending their consumption in the range of 500-3.500 W. Fig.11.7 shows how the EV consumption range is considerably wider in the case of urban conditions, being up to c.a. 115% of the standard 800 W consumption value for the NYCC, against the maximum c.a. 45% variation range of the WLTC.

Table.11.2 summarizes the EV consumption values calculated (E), in kWh/100km, for the different driving cycles analyzed. the importance of the auxiliaries over the TTW EV total consumption can be derived from these results.

From eq.11.6, the baseline of the ICEV emissions that will be used to compare each different driving cycle is presented in Table.11.3. Similarly to the EV case, the best results are found in highway driving conditions and the worst in urban conditions. However, larger variations between urban and highway driving conditions are obtained for the case of the ICEV.

In Fig.11.8, the annual GWP of the EV under the WLTC drive cycle and for various auxiliaries' consumption values is presented. It can be observed that the values fluctuate from 1.500 $kgCO_2e$. to 2.700 $kgCO_2e$. Considering an 8 year EV life, this results in total GWP ranging from c.a. 12.000 $kgCO_2e$. to 21.600 $kgCO_2e$. These values are consistent compared to the results obtained within the FSEM project [143], where, using the German electricity mix and considering 12 years EV lifetime and 14.300 km per year, emissions reached up to 30.000 $kgCO_2e$., or either 11.000 $kgCO_2e$. when using only renewable energy sources.

From the results presented in this section, a comparison between the EV and ICEV consumption values can be performed, for each of the driving cycles and under the wide range of

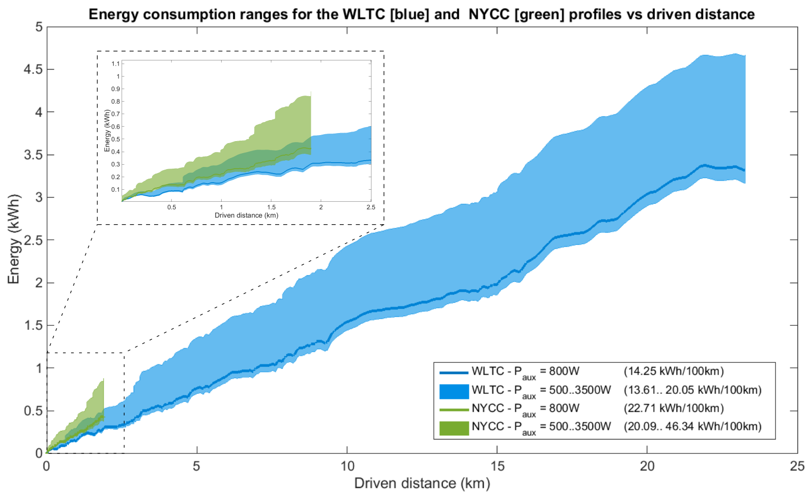


Figure 11.7: Energy consumption variation under different auxiliaries' consumption values.

Table 11.3: WTW emissions (in $gCO_2e./\text{km}$) under different driving cycles for the ICEV

Cycle	Emissions ($gCO_2e./\text{km}$)	Variation vs. WLTC
NEDC	132	92%
WLTC	144,15	100%
US06	146,02	101%
HWFET	82,41	57%
NYCC	265,33	184%
UDDS	128,53	89%

auxiliaries' consumption values already described. The electricity mix threshold values are calculated by means of eq.11.7 in order to determine the energy generation emission values for which EV and ICEV consumption are equalized. These threshold values can be then compared with the current electricity generation mix values of the European countries considered, as shown in Fig.11.9. In this figure, the colored range represents the effect of the auxiliaries, being the lower limit the one corresponding to the higher auxiliaries' consumption (3.500 W) and the upper limit the one corresponding to the lower auxiliaries' consumption (500 W). The colored line represents the results obtained for the standard 800 W auxiliaries' consumption value. Additionally, as each country has different temperatures, the use of auxiliaries' (mostly air conditioning or heating) might diverge from one to another, which is also represented in Fig.11.9 in a grey line. Note that this figure represents the allowable emissions range associated to energy generation for the EV to be environmentally profitable against an ICEV. Hence, the higher the energy consumption value is, the lower the energy generation emissions can be, for the EV to represent any environmental improvement, and vice versa.

From this Fig.11.9, the environmental benefits for each driving profile can be derived. Thereby, Fig.11.10 shows the percentage of GWP reduction achieved when using EVs on each country, depending on the driving profile and the auxiliaries' consumption range.

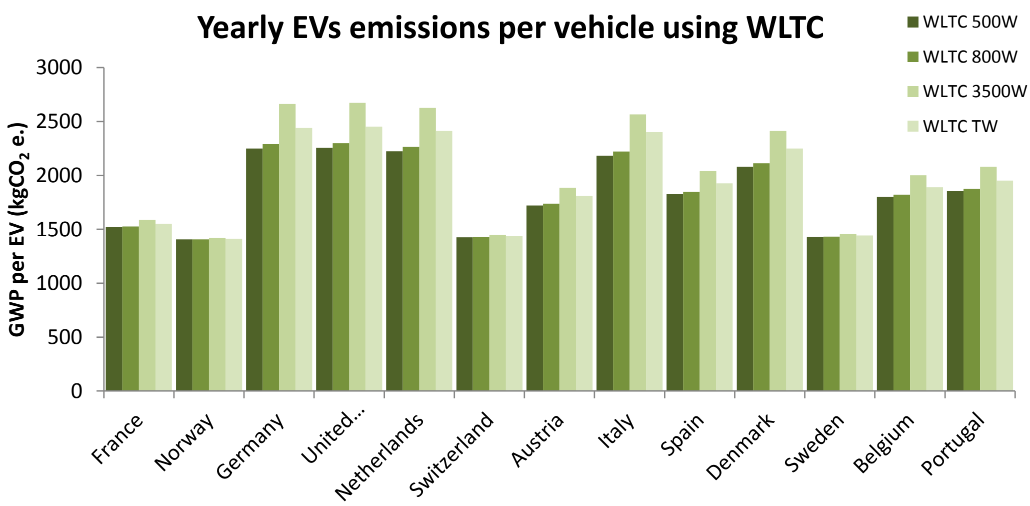


Figure 11.8: WLTC EV yearly emissions per country considering different auxiliaries load values. The black line corresponds to the emissions from an ICEV.

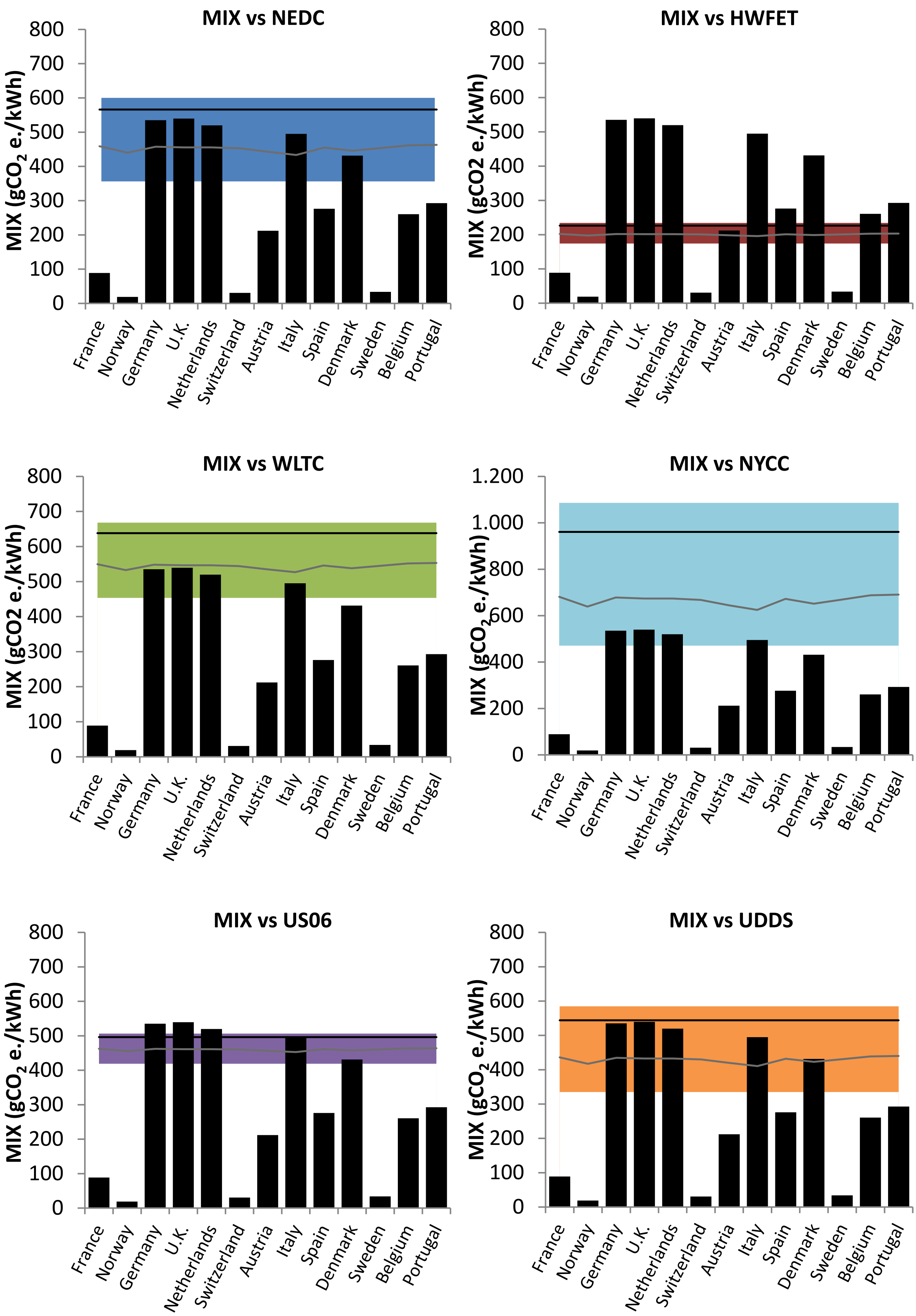


Figure 11.9: Electricity mix threshold to obtain benefits from the use of the EV instead of ICEV and the corresponding energy mix per country and by different driving cycles.

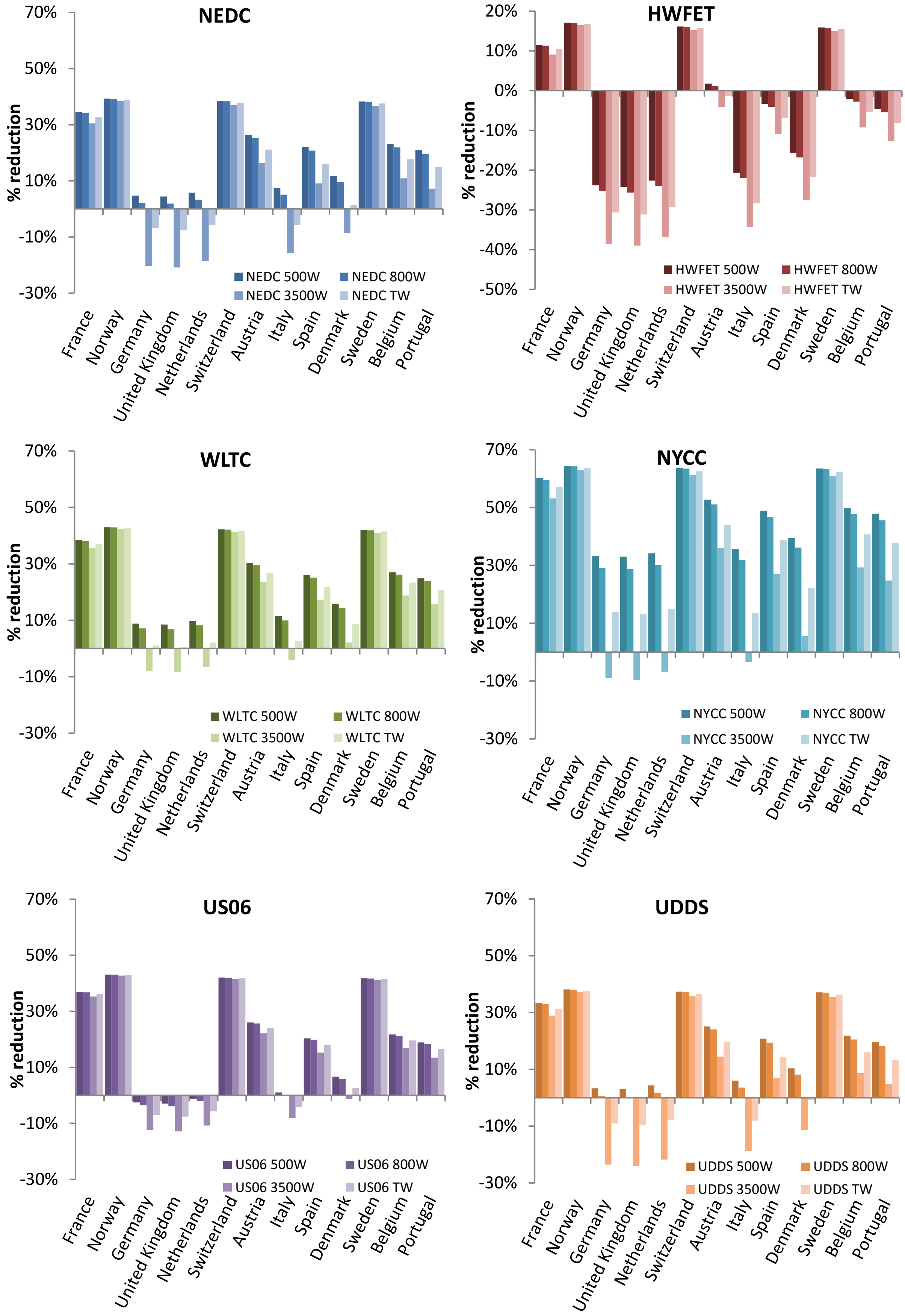


Figure 11.10: EV use environmental benefits or burdens per country classified by the auxiliary load and by different driving cycles.

11.5 Discussion

Results shown in the previous section depict a controversial scenario about which European countries are better suited, in terms of electricity generation infrastructure, to face the potential penetration of EVs in the upcoming years.

Although the penetration of EVs would suppose indirect environmental benefits, like a reduction of pollution in urban areas or lowering the dependence on fossil fuels, the potential benefits in terms of net GHG emissions is subjected to the emissions generated during the electricity generation phase. Hence, it is important to ensure a correlation between EV promotion and renewable integration strategies.

To facilitate the introduction of EVs, the European Union has provided incentives, plans, and strategies such as: European Commission 2010, Greater London Authority 2009, plan MOVELE, etc. [2]. However, only five countries in Europe (France, Norway, Germany, the U.K. and Netherlands) gather more than 80% of the EV sales in Europe.

Similarly, after the Kyoto protocol and the European 20-20-20 initiative, there have been incentives to enhance the introduction of renewable energy power plants and to promote cleaner energy generation. Nonetheless, the renewable energy penetration and the GHG emissions associated to electricity generation differ considerably from country to country, as shown in Fig.11.11.

In Fig.11.11(top) the number of EV sold and the GHG emissions associated to electricity generation per country can be observed. Similarly, in Fig.11.11(bottom) the electricity generation GHG emissions are related to the renewable energy share.

From this Fig.11.11, and considering the results obtained in Fig.11.9 and Fig.11.10, it can be derived that between the five EV most selling countries, only France and Norway have an electricity generation mix that ensures reductions in the net GHG emissions for the whole EV energy consumption range calculated in this study (which goes from 11,15 kWh/100km to 46,34 kWh/100km). In the case of France though, low electricity generation GHG emissions are achieved through a high penetration of nuclear power, despite its low renewable share. Thus,

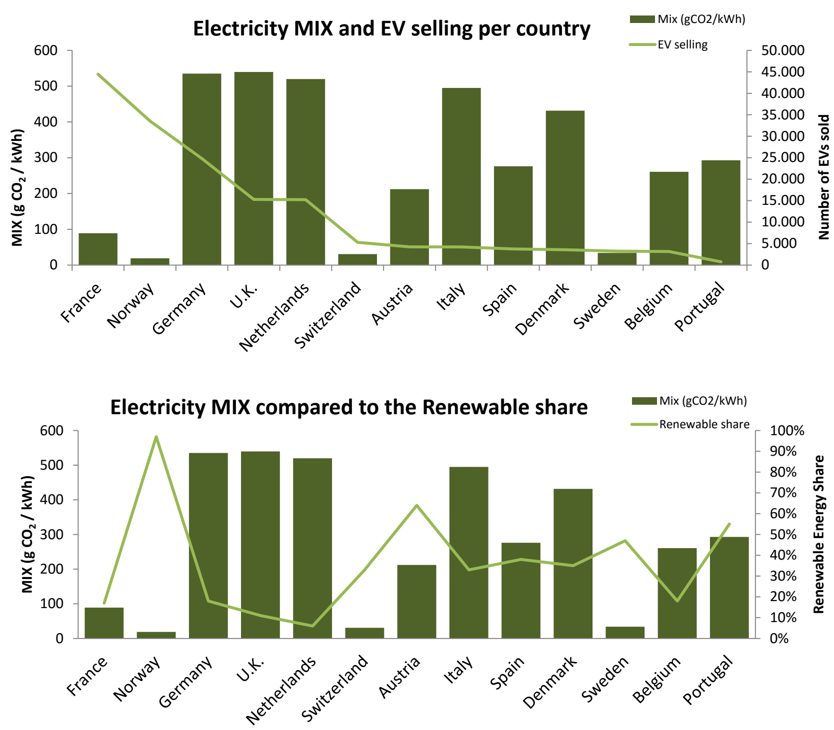


Figure 11.11: Emissions associated to electricity generation and EV sales (top) or renewable share per country (botom).

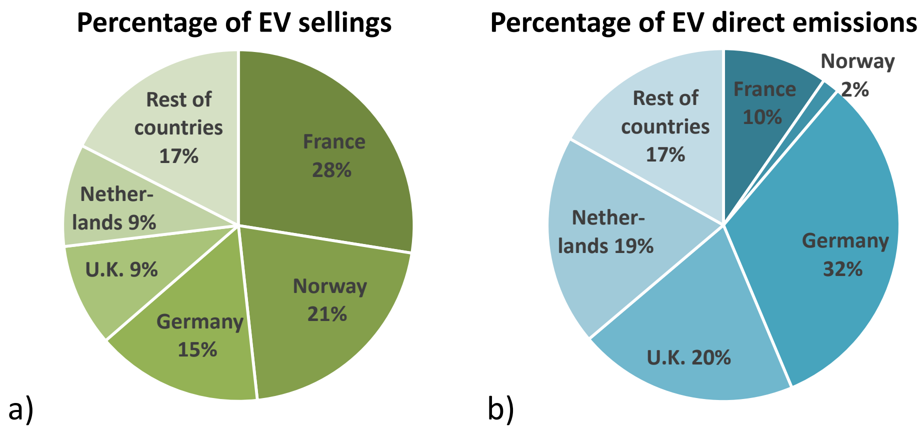


Figure 11.12: Share of EV sales in EU (a) and direct GHG emissions associated (b).

when trying to evaluate the total environmental impact of electro-mobility solutions, it is important to consider additional environmental parameters rather than only the GHG emissions, which should be addressed in future studies.

Considering EV market share, France and Norway gather almost 50% of the EV sales in Europe, being responsible of c.a. 12% of the total GHG emissions directly imputed to the use of these vehicles. On the contrary, Germany, U.K. and Netherlands, having just 33% of the EV market share in Europe, are responsible of 71% of the total emissions coming from EVs use, Fig.11.12.

Other countries like Switzerland, Austria, Spain, Sweden, Belgium or Portugal have big potential to accommodate EV penetration due to their low emissions associated to electricity generation and their high renewable share (especially high in the case of Spain and Portugal). These countries present reductions in the emissions under most of the analyzed conditions when using EV instead of ICEV, Fig.11.10. ICEV present lower GHG emissions only under highway conditions. In fact, most EVs, and particularly the reference vehicle considered in this analysis, are oriented to urban and sub-urban use, where they achieve considerably lower emissions. This supposes direct benefits on the reduction of local air pollution and on the net GHG emissions of the country.

Surprisingly, many countries in which the existing energy generation infrastructure is well prepared for the arrival of the EV are the ones providing fewer financial incentives to electro mobility; this is the case for Spain, Sweden, Austria or Portugal. The EV market analysis carried out by [145] pointed out some of the main factors for pushing forward EV penetration, being the income-per-capita a major factor, as shown in Fig.11.13. This fact evidences the higher necessity of institutional support in Spain and Portugal to facilitate a higher EV market penetration, which should be encouraged due to their appropriate electricity generation infrastructure, as already mentioned.

Norway is the country where the energy mix and the EV incentives are better aligned. Similarly, France is also encouraging the EV penetration, it is the sixth country with higher incentives, and additionally, local car manufacturers are strongly investing in electro-mobility. On the other hand, the U.K. is the fifth country providing higher EV incentives while it is the country having higher GHG emissions for electricity generation, and Germany is the third country in EV sales in Europe, mostly because it is the most populated country (EV market share is yet low, 0,34%) and there are almost no incentives to EV purchases. Besides Germany, U.K., Netherlands, Italy and Denmark, the rest of countries represent clear cases in which the promotion of renewable energy generation resources is highly advisable for the enhancement of the environmental benefits obtained from EV use.

According to our calculations, the energy generation GHG emissions threshold that provides

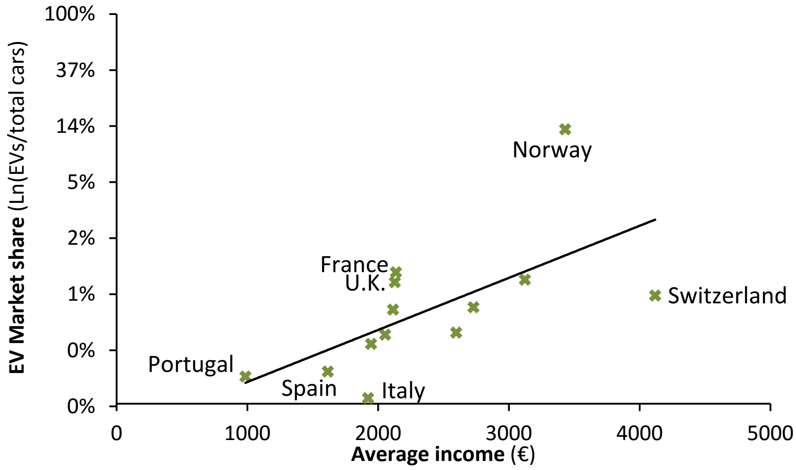


Figure 11.13: Relation between the EV market share and the national income per capita in EU.

net environmental benefits, for the whole EV energy consumption range, is c.a. 174 $gCO_2e.$/kWh. Comparably, if highway driving conditions are not considered, this threshold value rises to 356 gCO_2e/kWh.

11.6 Conclusions

The obtained results suppose a new tool to address the suitability of several European countries to the widespread use of EVs as an environmentally efficient alternative to conventional vehicles, and allows evaluating if the energy and transportation policies are environmentally aligned.

Similarly, the WTW analysis performed empowers the comparison between emissions associated to EV and ICEV use. However, a deeper analysis of other phases of the LCCO2 (e.g. maintenance or disposal) could be advisable in order to achieve more reliable results, although significant deviations from the results obtained in this study are not foreseen.

The results presented and discussed show an insight into the suitability of many European countries for the introduction of the EV. It can be concluded that for most countries covered in the analysis, current electricity generation mix is well suited to accommodate EV market penetration, and the usage of EVs will generally imply reductions in the net GHG emissions from the transportation sector. However, some of the most EV selling countries still feature highly pollutant electricity generation infrastructures, with low renewable energy resources shares. In those cases, an improvement of the infrastructure and increases on the renewable share should precede EV penetration, in order to ensure reductions in the net GHG emissions produced by both energy generation and transportation sector. In this work, it has been demonstrated that as long as the GHG emissions associated to electricity generation are kept below 174 $gCO_2e.$/kWh, environmental benefits will be obtained from the EV use under any driving condition.

It should be noted that even in the cases where the EVs penetration does not imply GHG emissions reduction, other benefits still may arise from the electrification of transportation, such as lower dependency on fossil fuels, environmental consciousness-raising or reductions on the air pollution in urban areas, which entails important consequences over human health.

In summary, the coupling between renewable share and EV penetration is clear, and hence, it is crucial to consider the energy generation sector before promoting EV penetration. For an EV to be environmentally beneficial, an environmentally respectful energy generation infrastructure is compulsory.

Chapter 12

Environmental Impact Considering Second Life Applications

"When a river overflows all we want is the water to decrease so it goes back on track".

Serge Latouche.

12.1 Introduction

Air pollution, dependency on fuels of finite supply, climate change and the increase of energy cost are some important challenges of the present world. These concerns are aggravated by transportation and power generation sectors since they are the main consumers of fossil fuels and responsible for most of the GHG emitted in the atmosphere.

The transportation sector has found in the technology of EV an emerging solution for these problems that have gained importance during the last decade. This transition to electrified transportation is being facilitated by the European Union directives restricting the emissions coming from transportation as well as the recent advances in Li-ion battery technology.

The main difference between a vehicle using electric power and a common internal combustion engine is the energy source. While the former uses crude oil derivatives stored in a tank, the latter converts stored electrochemical energy into electrical energy. This change forces car manufacturers to adapt all the traction, control, security, and refrigerating systems [137]. This results in a lighter traction system, a smaller electric motor and no gearbox, but also an overall weight increase of around 25% due to the battery system and all the electric and electronic additional components.

Although EV has no tailpipe emissions, its well-to-tank energy efficiency, coming from the electricity generation and distribution to charge the EV battery, might even be less performing than that of internal combustion engine vehicles [165]. Therefore, most of the LCAs point out the relevance of the electricity generation mix to identify the environmental impact of the EVs during the use phase [139], [136].

Additionally, an environmental impact increase of around 50% during the EV production phase has also been identified, being the battery manufacture responsible for more than 40% of this impact [135]. Aware of this setback, some car manufacturers have started to conceive the EV production as a whole environmentally friendly industry. For example, some companies are promoting the use of natural lighting and ventilation, solar panels, and rainwater harvesting in their production plants [166].

On the economical side, the battery is the principal hurdle for EV competitiveness as its fabrication cost represents around 30 to 40% of the final EV price. This causes an important cost increase for the consumer. In order to solve this drawback, car manufacturers use different strategies to stimulate EV purchases. For example, Renault and Nissan offer a battery renting alternative, reducing the selling price, while other companies, like the joint venture 4R-energy, are focused on battery 2nd life strategies to recover some incomes from the battery re-selling or from the profit obtained thanks to this life enlargement.

The study of the 2nd life of an EV battery cannot be dissociated from the battery performance during its use in an EV, the safety of the battery at the end of its life, and an accurate understanding of the loss of capacity. Therefore, in this study, we analyze the environmental impact of the 2nd life of an EV battery in eight stationary scenarios. The obtained results have been added to the GWP from the first life. An overview of the different battery chemistries used for EV applications as well as their main degradation mechanisms are also presented. A correlation between the materials degradation and the 2nd life applications is proposed.

12.2 Methodology

There are many environmental impacts studied in the LCA of EV, such as climate change, resource depletion, human toxicity, and eutrophication among others. However, the GWP, expressed in kilograms of carbon dioxide equivalent (kg CO_2 e.), is the most common environmental indicator used for the LCA of EVs for its simplicity and overall impact comprehension [137]. The scarcity or critical reserves of determined materials, such as lithium, will have no impact on our analysis because only reused EV batteries are considered in this study. Additionally and considering that there are many possible 2nd life applications, the use of the carbon footprint or the GWP as environmental indicator is thought to be the most indicated parameter in order to achieve comparable results. Therefore, the life cycle based on the CO_2 emissions ($LCCO_2$) methodology will be followed.

The $LCCO_2$ results strongly depend on the methodology and the defined system boundaries. In this chapter, the boundaries include the first and 2nd life of EV batteries. The assessment of the 2nd life will be evaluated considering different case studies of battery re-use. Additionally, to procure a wider comprehension of the environmental impact reduction caused by the battery re-use, a survey of the different electrode materials forming the batteries will be done, incorporating the study of their potential for 2nd life use.

Even though most of the electrified vehicles are hybrid cars using Nickel–Metal Hydride (NiMH) batteries, their power and energy characteristics are too low for most of the stationary applications [12]. At the end of the hybrid vehicle life, the SOH of these batteries is very variable and well beyond the 80% defined for pure EV batteries before recycling [85]. For these reasons, only the Li-ion batteries that have been used in an EV are considered, while NiMH batteries are not included.

Fig.12.1 describes the complete $LCCO_2$ boundaries of an energy storage stationary application using a 2nd life EV battery. It is the result of the combination of two existing approaches: $LCCO_2$ of an EV and $LCCO_2$ of a battery in a stationary application.

- $LCCO_2$ of an EV: This approach defines the system boundaries of an EV that has a battery used only in the EV. The boundaries of this assessment involve the battery and car production phases (including the GWP impacts of materials acquisition all around the globe and the transportation between phases), the EV use and dismantling, and the battery recycling phases (Fig.12.1 until the end of the first life). From different European-funded projects (UMBRELA FSEM and THEMLA) ([143], [139], [142]) and articles [162], it has been stated that the GHG emissions of an EVusing the average UE electricity mix (421 g/kWh) is around 35.000 kg CO_2 e., being the EV production responsible for 11.000 kg CO_2 e. Although these results might substantially change according to the electricity mix used, the average EU mix is used to facilitate the comparison.

- $LCCO_2$ of a battery in a stationary application: This approach defines some possible stationary applications where EV batteries can be used according to their physical and functional specifications (from 8 to 25 kWh and 80 kW max. power). Therefore, only small stationary applications will be studied (Andrew 2009). Some of these applications, such as solar-powered island systems, are nowadays using new lead-acid batteries. In these cases, the study will compare the impact reduction of substituting these batteries by re-used Li-ion batteries as shown in Fig.12.1. Using the LCA2GO software, and comparing with the literature [167], it is assumed that the GHG emitted by the fabrication of a lead acid battery are 60% of those emitted by the fabrication of a Li-ion battery with an equivalent capacity. However, their lifetime is reduced by 2,5 times (Teodorescu et al. 2013). In order to do a proper $LCCO_2$ analysis, the efficiency of the different elements involved in the study should be considered. For the calculations, the inverters are assumed to have an efficiency of 90% [109] and the lithium batteries have around 90–95% of charge–discharge efficiency [168]. On the other hand, lead-acid batteries have an efficiency of around 80%

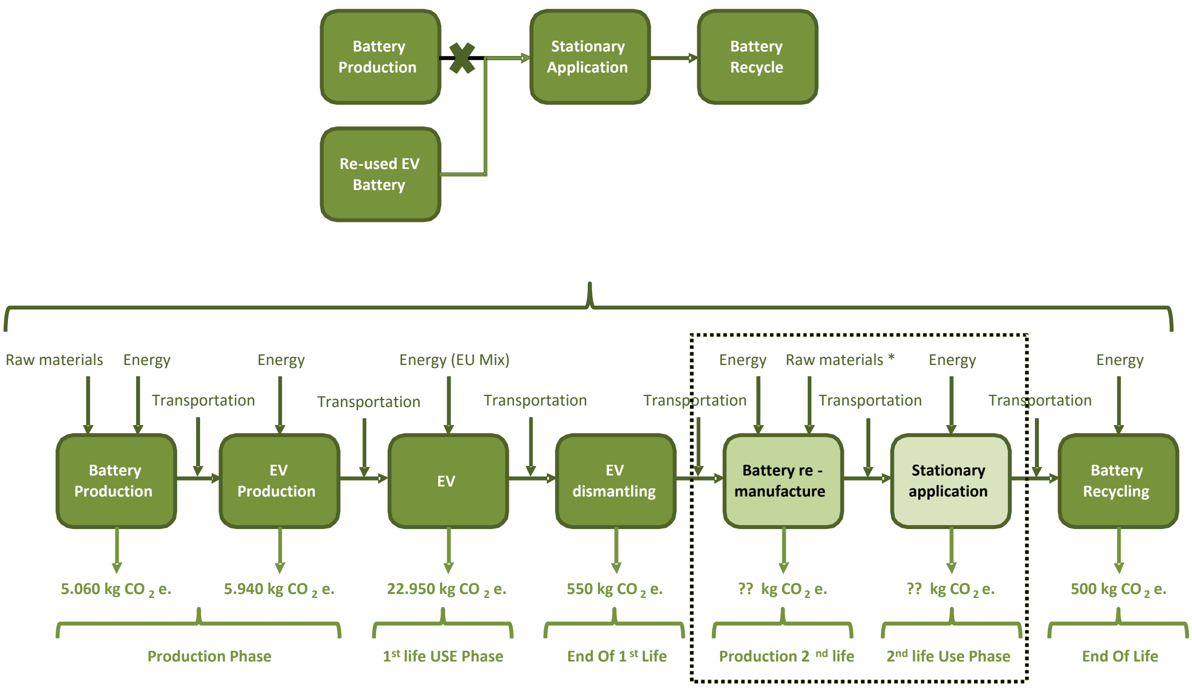


Figure 12.1: Description of the $LCCO_2$ system boundaries of a storage stationary application using an EV 2$^{\text{nd}}$ life battery instead of a new one.

* *The raw materials for the battery re-manufacturing or repurpose are considered negligible because of its low impact.*

[15], [169]. Consequently, the overall charge–discharge cycle efficiency is considered to be 0,7 when using Li-ion batteries and 0,6 when using lead-acid batteries.

- $LCCO_2$ of a stationary application using an EV 2nd life battery: Combining the two previous approaches, the complete system boundaries for the first and 2nd lives of an EV battery are obtained. These system boundaries are presented in Fig.12.1 with the addition, before the recycling phase, of the 2nd life phases in the common $LCCO_2$ of an EV (represented by a dashed square). These phases are the battery re-manufacture an 2nd life application. In this chapter, we will maintain the same EU mix for the energy exchanged with the grid during the 2nd life. This final approach is the one used for the calculations all along the study.

Our new approach involves two additional transportation steps that need to be taken into consideration; these steps include the battery transportation from the EV dismantling place to the battery remanufacturing plant and from the remanufacturing plant to the 2nd life application destination. In both cases, the generated emissions derived are calculated similarly.

The transportation of the battery will be done by truck, and only one battery will be transported at a time. This assumption is most likely not going to evolve much in the near future as the EV market is below 1% in most European countries. Hence, the average trip distance for the battery acquisition is assumed to be 1.000 km. The derived GHG emissions from this trip are 317 kg CO_2 e. As the studied 2nd life applications are expected to work with one battery only, all these assumptions can also be used for the battery delivery to the final destination. This value represents less than 1 % of the total emissions of an EV during its first life. Hence, despite logistic optimizations, not much improvement on the environmental impact will be obtained.

There are different ways to address the battery remanufacture processes: the direct re-use of the battery; the dismantle of the battery into modules to re-build it as a new battery pack adapted to the 2nd life application; and, finally, the dismantling of the battery at cell level to re-build it depending on its SOH. As shown in previous works, the best possibility to reach a positive economic balance is the direct re-use of the batteries without module manipulation [75]. Consequently, this option will be the one used in this study. The process of remanufacture entails a visual check, a capacity and pulse test to determine the SOH, and the few necessary adjustments to adapt the battery to the new application. The energy consumption in the remanufacture phase is calculated to be 27 kWh per battery check, which corresponds to 11,5 kg CO_2 e. that needs to be added to the previous values.

In order to obtain comparable results, it is important to define the Functional unit (FU) that will be used. In the LCA of an EV, the FU normally considered is the kilograms CO_2 equivalent emitted per range or per kilometer. However, in stationary applications, the FU generally used is kilograms CO_2 equivalent emitted per battery weight (kg), per battery capacity (Ah), or per energy (kWh) exchanged with the grid [167]. In this study, the kilograms CO_2 equivalent emitted per functional kilowatt hour will be used given that it has no sense to use kilometers, battery weight, or battery capacity for s2nd life applications. A functional kilowatt hour is defined as the energy (kWh) received by the consumer directly from the battery (not to confuse with the energy received from the grid or power source).

In the case of 2nd life applications, the factors that have a major environmental impact contribution are the battery lifetime, the energy source, and the system efficiency:

- Lifetime: The battery lifetime depends on the materials present in the battery and on the requirements of the application. The shorter the battery lifetime, the higher its environmental impact.

- Energy source and system efficiency: The pollution coming from the energy sources is essential for the sustainability; i.e., it is obviously cleaner to use solar panels than to burn coal. The efficiency deals with a similar issue; if a system is more efficient than another, the energy losses will be lower and, consequently, the environmental impact will be less.

The battery lifetime factor depends on the temperature (T),the charge and discharge requirements (C-rate), the average SOC, the number of cycles, and the DOD per cycle. These identified aspects can be linked to the capacity fade as presented in eq.12.1. From literature [123], [63], [36], [34], the Li-ion battery lifetime equations are obtained (eq.12.2), and considering the experimental data of these studies on specific Li-ion battery systems, which is the most common in EV batteries [86], the parameters are determined (eq.12.3). Hence, the battery lifetime can be predicted.

$$C_{Fade} = 1 - (C_{rate} factor) - (SOC and Temperature factor) - (Cycling factor) \tag{12.1}$$

$$\begin{aligned} C_{Fade} = 1 - (r(SOC,T) * I) - (a * V - b)10^6 * e^{\frac{c}{T}})t^{0,5} - \\ -(\frac{d}{C_{ini}(e - f * \frac{log_{10}(DOD)}{2})} Ah)) \end{aligned} \tag{12.2}$$

$$\begin{aligned} C_{Fade} = 1 - (r(SOC,T) * I) - (7,543V - 21,75)10^6 * e^{\frac{6.975}{T}})t^{0,5} - \\ -(\frac{0,15}{C_{ini}(6.000 - 3.000 * \frac{log_{10}(DOD)}{2})} Ah) \end{aligned} \tag{12.3}$$

Where $C_{\text{fade}}$is the capacity loss, $r_{(\text{i, T})}$ is the internal resistance, I is the current intensity, V is the battery voltage, T is temperature, C_{ini} is the initial capacity of the battery, t is the time elapsed, and Ah is the accumulated current discharged by the battery.

The lifetime of the battery can be estimated from these equations by identifying the variable parameters from the 2$^{\text{nd}}$ life requirements. To facilitate the calculations, all these parameters were considered constant for monthly periods. For example, an application that has a daily DOD of 100% will have an average voltage corresponding to 50% SOC, and the Ah would be equal to the battery capacity multiplied by the number of days per month, i.e., 37 Ah (battery capacity) 31 days=1.147 Ah.

The stationary applications can be classified according to the beneficiaries, which are basically the electric companies and the end users. The electric companies are paying special attention to the developments on storage systems providing energy services, such as "area regulation", "transmission and distribution deferral", and "power quality" among others [16]; [43], [42]. However, these applications require high power and energy systems that imply the incorporation of hundreds of EV batteries [39] that are still not yet available. Therefore, they will not be assessed in this study.

This chapter is focused on single battery 2$^{\text{nd}}$ life systems which are the most suitable for end user applications. Considering the capacity and power specifications of the EV battery, three stationary applications have been determined. Each application has its particular battery cycling conditions:

- Energy arbitrage: In this application, the energy is bought at low fare rates (e.g., during the night) to recharge the battery and the accumulated energy is consumed during the periods when the electricity is more expensive (e.g., during the day) [39]. For the calculations, the European electricity mix is used. In this situation, the battery will be fully charged and discharged (close to 100% DOD).

- Island installations: In this application, the system will be connected to Renewable Energy Sources (RES) charging the batteries when the energy production excesses the demand, restituting it to the house when there is not enough energy production [168]. This represents an alternative to the actual systems using lead-acid batteries or fuel generators to power up the installations. In this situation, the DOD of the battery will be around 50%.
- Autonomous use: In this application, the batteries are charged by the RES but the whole system is connected to the grid, providing an energy support in case of a lack of generation from the RES [170]. In this case, the DOD of the battery will also be around 50%.

Based on these three stationary applications using 2nd life batteries, the results were compared with different alternatives to power up each application, which go from using leadacid batteries to an electricity diesel generator, obtaining the eight analyzed scenarios described in Table 12.1.

The battery lifetime is obtained from eq.12.3 considering the first and 2nd life. This way, after using the battery during 10 years in an EV, we obtain a SOH of 78% at the end of the first life. Then the battery will continue working in the 2nd life application until it achieves a final SOH of 60%. In the studied cases, this limit corresponds to 8 or 20 years of additional use depending on the 2nd life application. This difference in lifetime is explained by the different requirements between island and autonomous applications corresponding to a DOD of 50 and 100%, respectively, and consequently, on C-rate.

Finally, in order to properly identify the environmental impact of the battery re-use, a comparison of the impact loads of the production, uses, and end-of-life phases on a battery lifetime (considering first and 2nd life) will be presented.

To present growing opportunities, future expectations, and research recommendations, an analysis of the materials used in the actual EV battery cells and their properties will be offered.

Table 12.1: Study cases and scenarios analyzed

Scenario	**Stationary application**	**Description**	**Battery**	**Lifetime (Years)**
Base case (No 2nd life)	None	No battery is used in this option. The EV is directly dismantled after 10 years and, during the following 20 years, the average energy used in a house is taken from the grid.	No	10+20
RES	Autonomous use	No battery is used in this option. The EV is directly dismantled after 10 years and, during the following 20 years, the average energy used in a house is taken from renewable energy systems.	No	10+20
Island fuel generator	Island installation	No battery is used in this option. The EV is directly dismantled after 10 years and, during the following 20 years, the energy is obtained from a common diesel generator.	No	10+20
Energy arbitrage Pb	Energy Arbitrage	The EV is directly dismantled after 10 years and, during the following 8 years, the energy arbitrage is done with new Lead-acid batteries (three battery packs are needed to cover the 8 years expected for the equivalent EV Li-ion re-used battery).	Lead-acid battery	10+8
Island Pb	Island installation	The EV is directly dismantled after 10 years and, during the following 20 years, the energy is obtained from RES and it is connected to new Lead acid batteries (3 batteries are needed to cover the 20 year life-length expected for the equivalent EV Li-ion re-used battery).	Lead-acid battery	10+20
Energy arbitrage	Energy Arbitrage	After the 10 year use in the EV, the battery is re-used for energy arbitrage in a house during 8 more years. The energy is taken from the electricity grid.	Re-used Li-ion battery	10+8
RES 2nd life	Autonomous use	After the 10 year use in the EV, the battery is re-used during 8 years more for RES storage in a house connected to the grid for sporadic energy support.	Re-used Li-ion battery	10+8
Island 2nd life	Island installation	After the 10 year use in the EV, the battery is re-used for over 20 years more in island conditions connected to a RES.	Re-used Li-ion battery	10+20

12.3 Materials

Li-ion battery technology can be divided into different chemistries presenting their own characteristics and advantages [171]. Over the last decades, tremendous progress has been done in developing cathode, anode, and electrolyte materials, which represent the most important components of Li-ion batteries and at the same time will determine the battery performances. In this work, the study is mainly focused on the cathode and the anode materials as they are the source of many degradation processes. The electrolyte is also a key component as it has many limitations such as the temperature and voltage window. However, organic electrolytes incorporate many additives which play a crucial role in improving the battery performances. These additives are usually not made public in order to preserve the competitiveness of the battery manufacturers. Therefore, electrolytes will not be considered in the study. In this section, an overview of the most common cathode and anode materials will be done, describing the most remarkable advantages and their main drawbacks.

Among the cathode materials, spinel oxides, olivine phosphates, and layered oxides have attracted a significant interest for applications in EV [172]. Table 12.2 gathers the most commonly used cathode materials and their main characteristics [173], [174]; [175].

Currently, one of the most popular cathode compounds is the spinel $LiMn_2O_4$ (LMO) as it presents many advantages such as low cost, non-toxicity, abundant manganese resources, simple production, and excellent safety [176], [177]. Manganese appears as Mn(III) and Mn(IV) active species, which offers the possibility of a redox reaction by insertion and extraction of Li+ ions through the tridimensional channels of the framework. Although LMO and its variants have many advantages, they still suffer from capacity fading during cycling [178]. The spinel LMO suffers from manganese dissolution in the liquid electrolyte. The surface of the LMO particles is especially vulnerable to chemical reactions. This issue is aggravated by the Jahn–Teller distortion of Mn(III) ions and the change in crystal lattice arrangement during cycling. This effect has been highlighted when cycling the battery at 60C and promotes an early loss of capacity of the battery.

On the other hand, since 1997, LiFePO4 (LFP) olivine has become a promising material for cathodes due to its good electrochemical properties with a very flat potential profile at 3,45 V vs. Li/Li+ [179]. The lithium ions move through tunnels that are formed in the structure. Additionally, LFP presents low cost, non-toxicity, thermal stability, and environmental friendliness compared to other compounds. However, this material has low energy density due to a limited operating voltage, and it has a poor rate capability, which is limited by the one-dimension ionic conductivity and poor intrinsic electronic conductivity.

Regarding layered structures, $LiMO_2$ materials (where M is one or more transition metals) are considered as a good choice for cathode materials because of the MO_2 slabs in the structure

Table 12.2: Main characteristics of common materials used as cathode for EV applications

Type of Material	**Composition**	**Operating Voltage vs Li/Li+ (V)**	**Capacity (mAh/g)**	**Energy density (Wh/kg)**	**Safety**	**Cycle life**
Spinel	$LiMn_2O_4$	4,0-4,2	148	592-620	Good	Average
Olivine	$LiFePO_4$	3,45	170	585	Good	Average
Layered	$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$	3,85	276	1.062	Poor	Good
Phosphate	$Li_3V_2(PO_4)_3$	3,8	197	749	Good	Good

Table 12.3: Main characteristics of common materials used as anode for EV applications

Type of Material	**Composition**	**Operating Voltage vs Li/Li+ (V)**	**Capacity (mAh/g)**	**Energy density (Wh/kg)**	**Safety**	**Cycle life**
Graphite	C	0,1	280–330	28-33	Poor	Average
Spinel	$Li_4Ti_5O_{12}$	1,55	160	248	Good	Good

enabling good lithium ion insertion/extraction. Although the conventional layered oxide $LiCoO_2$ has been commercialized as a Li-ion battery cathode for 20 years, it can only deliver about 140 mAh/g capacity, which is half of its theoretical capacity [180]. Consequently, partially substituted compounds were developed to increase the stability and the capacity values of this material. Nowadays, Ni and Mn transition metals are used for EV application. Thus, NMC ($LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$) materials are a better choice to use as cathode for high-performance Li-ion batteries (Thackeray et al. 2005). The Li-Ni disorder in the lattice is a major factor affecting the material rate capability. In this sense, the presence of Co can help to reduce the Li^+/Ni^{2+} exchange. Moreover, NMC materials have a moderate thermal stability and tolerate fast charging rates. Other layered compounds have gained interest for EV applications; it is the case of Ni-rich layered oxide (Shizuka et al. 2005), $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA), which has a high usable discharge capacity of 200 mAh/g [181]. However, it has been reported that the capacity fade of this material may be severe at elevated temperatures (40–70 °C) due to SEI growth and micro-crack formation at the grain boundaries, which can lead in some cases to the explosion of the battery [182].

Given the merits of high power density, safety, long cycle life, and good rate capability, another candidate for cathode materials used in EVs is the monoclinic phosphate $Li_3V_2(PO_4)_3$ Lithium vanadium phosphate (LVP) [183]. The three-dimensional structure of this phosphate allows the extraction of all three lithium ions from the lattice with a theoretical capacity of 197 mAh/g in the voltage range of 3,0 to 4,8 V. However, the intrinsic electronic conductivity of this material is low [184]. In this sense and in order to improve its conductivity, the substitution of vanadium by other metal cations has been proposed as it also improves its structural stability [185].

With respect to anode materials, graphite is the most generally used active material even though some car manufacturer shave preferred the use of the lithium- and titanium based spinel anode. The main characteristics of these materials are shown in Table 12.3 [186].

As mentioned before, graphitic carbon has been predominantly employed as the anode material of choice due to a number of desirable characteristics, which include low cost, easy processing, and chemical stability. In addition, it has a desirable electrochemical profile [187]. However the Li-ion insertion/extraction during the charge cycle induces a significant volumetric gain (around 9–10%) which places stress on the electrodes and could be determinant for cycling stability. Furthermore, with a low operating voltage of around 100 mV (vs. Li+/Li), the graphite anode may react with the electrolyte, resulting in lithium metallic deposition. This not only reduces the battery performances but poses serious concerns in terms of safety, such as thermal runaway which could be aggravated at low temperature.

To overcome these issues, the spinel $Li_4Ti_5O_{12}$ (LTO) material has become a promising alternative anode [97]. This compound shows excellent structural stability of almost zero-strain during lithium ion insertion/extraction, leading to high rate capability and reversibility during discharge–charge cycling. It also provides a stable voltage of 1,55 V against a lithium electrode with a theoretical capacity of 175 mAh/g and an actual discharge capacity of over 160 mAh/g.

Furthermore, $Li_4Ti_5O_{12}$ is cheap, non-toxic, and easier to produce than other alloy-based anodes. On the other hand, regarding the reaction mechanism of this spinel, it has been reported that lithium reacts according to the kinetic reaction:

$$Li_4Ti_5O_{12} + 3Li^{++}3^e = Li_7Ti_5O_{12} \qquad [188], [189] \qquad (12.4)$$

The rate capability of $Li_4Ti_5O_{12}$ is relatively low, as the poor electrical conductivity and slow lithium-ion diffusion lead to large polarization at high charge–discharge rates.

All the exposed electrode materials are the main ones used nowadays by car manufacturers and are detailed in Lu et al. [113]. The dominant cathode material used for EV batteries is LMO as it is used by Nissan, Chevrolet, and Renault, associated with a graphite anode. Tesla and Subaru used the same anode associated with NCA or LVP, respectively. Honda has developed a vehicle using the spinel LTO chemistry as anode, associated with the layered oxide NMC spinel.

There are many choices of battery materials for EV applications, and each battery manufacturer will select the compounds that are most appropriate for their vehicle requirements. The fast improvements on the Li-ion battery topic force car manufacturers to be flexible and open to any new technology.

12.4 Results and discussion

In this section, the GWP analysis will be performed for the eight different scenarios presented in Table 1. The evolution of GHG emissions for the first and 2nd life of batteries is presented in Fig.12.2. The 35.000 kg CO_2 e. emitted during the first life in an EV is considered the same in all the case studies; this impact corresponds to the sum of the black and dark gray parts in Fig.12.2. On the other hand, the GHG emissions of the battery at the 2nd life diverge depending on the energy source and application. To analyze these results, it is important to take into

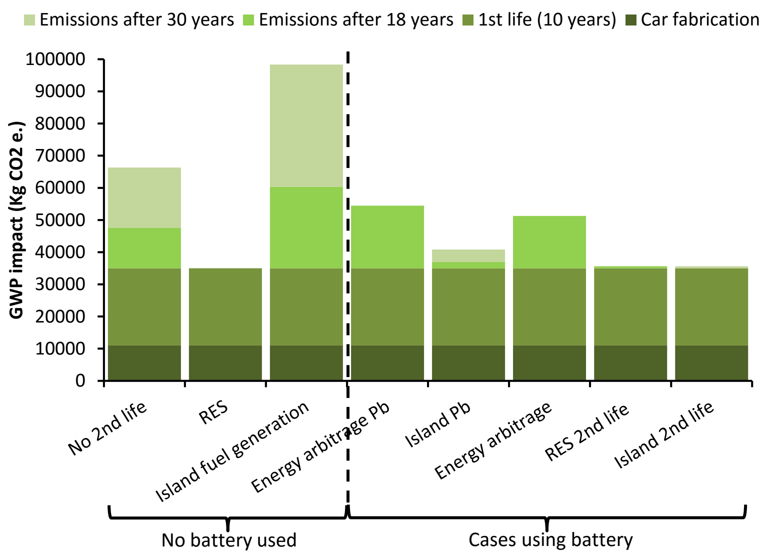


Figure 12.2: Global Warming Potential (GWP) of an EV considering its battery 1st and 2nd life.
The black stripe represents the EV fabrication impact. The dark grey corresponds to the first life in EV (years 0 to 10). The medium dark grey represents the first 8 years in 2nd use (years 10 to 18).The soft grey corresponds to the rest of 2nd life until battery end-of-life (years 18 to 30).

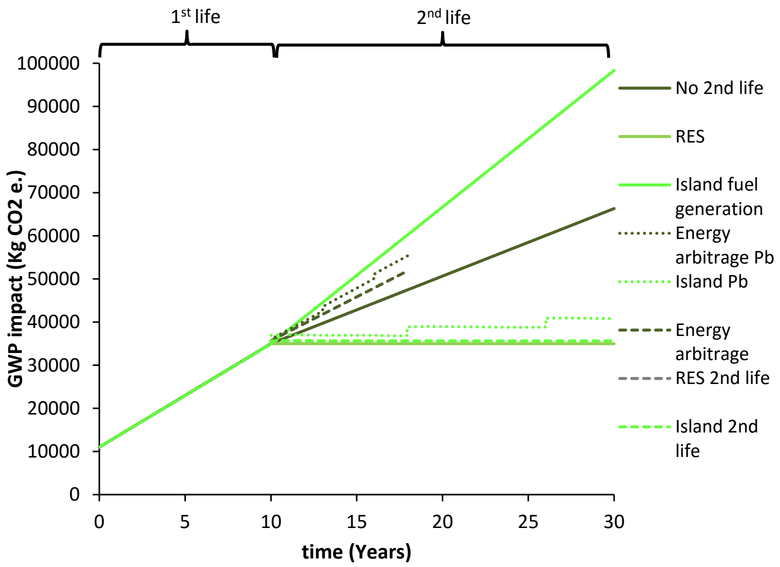


Figure 12.3: GWP as a function of time for the 8 scenarios studied.
The continuous, dotted and dashed lines represent the cases without battery, with Lead-acid batteries and with 2nd life Li-ion battery respectively.

consideration the lifetime of the battery. As it has been mentioned in the "Methods" section, all batteries do not have the same lifetime during their 2^{nd} life. Based on the 2^{nd} life endurance of Li-ion batteries (deduced from eq.12.3), the battery durability on autonomous and on energy arbitrage stationary applications is 8 years, while in the rest of cases it can last up to 20 years. This could be partly attributed to the harder cycling conditions described in the methodology. Therefore, the total lifetime will be 18 years for the batteries that are used in autonomous or energy arbitrage applications and 30 years for the other cases. The accumulated GHG emissions during these periods are identified with different shades of gray in Fig.12.2.

Additionally, from Fig.12.2, it can be observed that during the first 18 years, the highest impact is found in the island fuel generator case with 60.341 kg CO_2 e. emissions. The use of batteries for energy arbitrage releases more than 52.000 kg CO_2 e., proving that the pursuit of economical profit does not necessarily bring any environmental benefit. The increase of GHG emissions for these cases is higher than that of the base case due to the efficiency and energy losses of energy storage systems.

It is visible how the GWP increases if the employed energy source has a pollutant character. In order to enable a comparison between the GWP and the durability of the battery for each application, the evolution of emissions as a function of time is presented in Fig.12.3. The continuous, dotted, and dashed lines represent the cases without batteries, with lead-acid batteries, and with 2^{nd} life Li-ion batteries, respectively.

It can be observed that the emission's slope changes after the first life of the battery in the vehicle (year 10 in Fig.12.3) proving how it strongly depends on the 2^{nd} life application. Using this type of representation, the variation among the different battery technologies is more visible. The first difference is related to the steps found in the dotted curves using lead-acid battery systems. These steps are caused by the battery replacement due to its shorter life length. The second major difference is the softer impact slope of Li-ion battery systems, which could be ascribed to their higher efficiency.

Another way to identify the environment impact of the eight different cases studied is to calculate the total kilograms CO_2 equivalent emitted per functional kilowatt hour (Fig.12.4). This representation shows the net GWP per kilowatt hour at the battery end of life, providing a clear understanding of the overall impact behavior. The line between columns is the impact

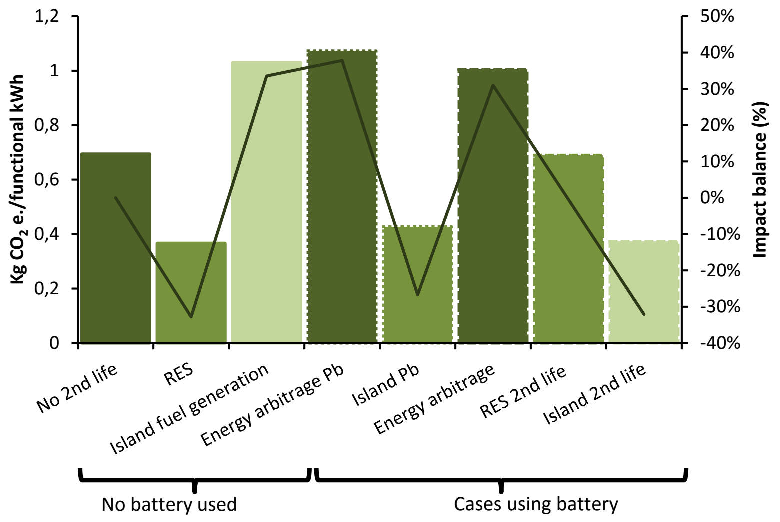


Figure 12.4: In columns: GWP per functional kWh for the different cases at the end of the battery lifetime.
The red line corresponds to the impact balance compared to the base case.

balance, which represents the variations of the GWP per functional kilowatt hour, taking the base case as reference.

Consequently, if the emissions per functional kilowatt hour are lower (i.e. RES), the balance will be negative. On the other hand, a positive balance means that the environmental impact is higher than without battery re-use. It can be observed that the use of batteries (no matter the technology) for energy arbitrage has more than a 30% GWP increase. Moreover, in the case of lead-acid batteries, the impact balance is even higher than the direct fuel combustion, while the re-use of EV batteries in island installations (island 2nd life) has a reduction of 32%. Therefore, it is not environmentally desirable to use batteries for energy storage if no renewable energy sources are used.

In this diagram, it can be observed that the cases leading to the worst environmental impact are the island fuel generation and energy arbitrage. In addition, the use of Li-ion batteries also provides better results than the ones using lead-acid batteries. Surprisingly, the results after 30 years of the base case with the European energymix and no battery re-use has a ratio of 0,694 kg CO_2 e./kWh which is similar to the 0,689 ratio found for the re-use of EV batteries in autonomous installations using RES. This situation is the result of different battery lifetimes, and it is explained by the evolution of the kilograms CO_2 equivalent/kilowatt hour ratio through time (Fig.12.5).

Before the battery starts to be used in an EV, it has already emitted more than 4000 kg CO_2 e. due to its fabrication and installation processes. From this point of view, as the battery provides a higher amount of kilowatt hours, the ratio of emission per functional kilowatt hour will be lower. Fig.12.5 shows that steeper slopes do not directly correspond to a lower final ratio at the end of life. In fact, the slopes of the energy arbitrage cases are steeper than the island fuel generation. However, as the energy arbitrage cases last 12 years less than the island fuel combustion with a diesel generator, they have a similar value at the end of life. This same situation is found in the RES system in autonomous applications.

Note that all the cases start at the beginning of the 2nd life with 1,6 kg/kWh. This value has been obtained dividing the emitted 35.000 kg CO_2 e. by the 22.500 kWh used during the vehicle's 1st life.

As a general observation, the longer the battery endures, the lower its impact per functional kilowatt hour will be. In this sense, it is important to note that the capability of a battery to be used in a 2nd life application strongly depends on the degradation of the battery at the end of the EV life (i.e., for a capacity below 80%). It is therefore a priority to understand the degradation mechanisms of the battery components in order to determine its potential for re-use. The main degradation mechanisms of the electrode compounds presented previously are described in the following section.

During the 2nd life, the EV batteries will be cycled under different conditions according to the selected application. It has been previously calculated how these cycling conditions affect the battery lifetime. Indeed, when the battery is used for energy arbitrage or in autonomous application, it suffers a nominal capacity drop from 80 to 60% in only 8 years. On the contrary, the lifetime of a battery connected to an island 2nd life system reaches 20 years due to more favorable conditions of use. This difference is mainly due to the cycling conditions and more particularly the DOD of the charge/discharge cycles. An adequate choice of the battery chemistry in relation with the working condition is necessary to improve the battery lifetime, minimize the risks for the end users, and therefore reduces the environmental cost.

For the energy arbitrage application, the battery will be fully charged during the night and fully or partially discharged during the day. In this case, full charges and discharges of the battery should be considered, equivalent to 100% DOD: the entire electrochemical profile. For this type of application, it is important to choose an electrode chemistry able to withstand a large voltage amplitude. It is well established that graphite electrodes may easily form lithium dendrites at high C-rates or when reaching a low voltage of discharge [190]; [191]. The use of graphite electrodes for this energy arbitrage application will further promote the formation of dendrites and lead to a faster capacity decay of the battery. Therefore, it is not advisable to use graphite as anode but another material presenting a higher voltage, such as LTO. Indeed, this spinel material shows better stability during the discharge as its electrochemistry restricts the voltage to 1,55V, which is sufficiently high to prevent lithium platting. However, the use of LTO as anode will decrease the energy density of the battery and will definitely have cost consequences for the consumer. These observations will also be valid when using RES in autonomous applications as similar deep charge-discharge cycling profiles will be executed.

On the cathode side, any chemistry can be considered as each of them presents pros and cons. An established choice cannot be defined as easily as for the anodes. In terms of safety, it would be preferable to use LMO or LFP cathodes as they present a better stability than NMC [180]; however, the faster capacity fade of LMO will most probably be an important drawback for the

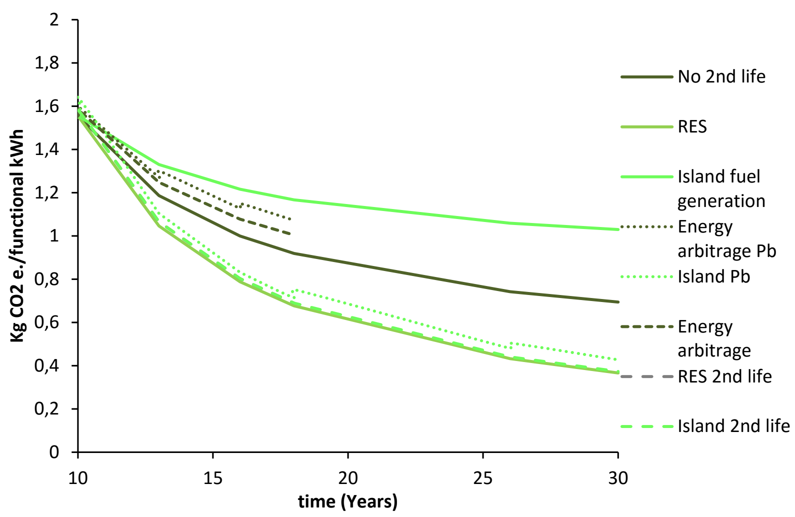


Figure 12.5: Evolution of the average kg CO2 e. emitted per functional kWh during the 2nd life in the different scenarios.

Table 12.4: Summary of the compatibility between the battery chemistry and potential stationary applications for 2nd life EV batteries.

	Cathodes				Anodes	
	LMO	LFP	NMC	LVP	Graphite	LTO
Energy arbitrage	+++	+++	++	+	+	+++
RES 2nd life	+++	+++	++	+	+	+++
Island 2nd life	+++	++	+	+++	+++	++

2nd life use. The use of the NMC cathode could also compensate the loss of energy density due to the high voltage plateau of LTO as NMC presents an energy density above 1.000 Wh/kg.

The island applications present another type of cycling profile. It is expected that the battery will rarely be fully charged or discharged. The battery will accumulate the energy depending on the availability of the renewable energy and will also use it directly for the house. In this sense, it is important to focus the chemistry of the battery towards materials enabling good cycling capability but discarding the properties at the end of charge and discharge. According to these constraints, both LTO and graphite can be present in the anode. The lower cost of graphite will clearly be an advantage of choice, and as the full discharge of the battery is not expected regularly, the degradation of the electrode due to the lithium platting will be limited. On the cathode side, the high voltage of LMO or LVP will be an advantage as it will reduce the DOD and the absence of nickel reduces the cost of the battery. All these observations are summarized in Table.12.4.

12.5 Conclusions

In this study, the $LCCO_2$ of an EV has been performed for different scenarios. These scenarios, mainly focused on the battery point of view, depend on the 2nd life of the battery in stationary application. Besides, an overview of the most relevant battery chemistries used for EV applications as well as their degradation mechanisms has been presented. The study reveals that the environmental impact per functional kilowatt hour decreases with the use of the battery.

Anyhow, from an environmental point of view, the use of batteries is only advisable in association with renewable energy sources. If that is not the case, the environmental impact caused by the losses derived from the energy storage should be added to the emissions coming from the pollutant energy source acting as a multiplier factor.

Nowadays, the improvements of the Li-ion battery performances for EV applications are mainly focused towards high energy and power density. However, cycling and calendar behavior are necessary to improve the re-use of the battery in a 2nd life application. As it stands, graphite is commonly used as anode among car manufacturers due to its low cost and good electrochemical performance. However, this material presents important degradation mechanisms such as lithium platting. Other anodes such as LTO could also be a candidate to the electrode material in the 2nd life use, but its high voltage prevents its development in EV batteries. On the cathode side, oxides and phosphates are widely used and reveal good stability upon cycling. LFP material presents good cycling stability whereas manganese-based electrodes suffer from a faster degradation that may be unfavorable for 2nd life use.

We observed that it is necessary to select the battery chemistry according to the secondary application of the EV battery. These applications are directly related to the energy source and will influence the battery charge and discharge conditions such as the working DOD: full charge–discharge cycles that consume the battery life length rapidly and partial charge–discharge cycles extending the battery life. However, a further investigation on the degradation of the electrode at the end of the 2nd life would be necessary to identify the most suitable systems.

Chapter 13

Conclusions

"Life, what is it but a dream?".

Lewis Carroll *"Alice in wonderland and through the looking glass"*.

During the last three years, being involved in several battery 2nd life projects with different partners and having the chance to participate in some energy storage symposiums, I saw that the interest of private companies, research institutes and local institutions in this type of solutions was (and is) increasing. Therefore, the first conclusion of this thesis is that, sooner or later, the EV battery reuse is going to be a fact, as it gives benefits to all actors in the mobility and energy sectors.

The study presented in this thesis provides the necessary information to face battery repurposing. Due to the EV battery complexities, it is not surprising that the first reuse initiatives are joint-ventures and cooperative projects between electricity enterprises and car manufacturers; yet no company dared to start a battery reuse business on its own taking more than one battery type. Therefore, the battery reuse is foreseen by the specialization on one battery type only in these first stages of innovation, even though many batteries are left to the concurrence. Thus, there is enough market for several companies to start!

Another conclusion is that, even if the price of new batteries continue decreasing in the following years, the 1/3 ratio difference in cost against repurposed batteries is going to be maintained. In fact, the repurposing cost analysis done in Chapter 5 gave some hints for future improvements in the re-manufacture industrialization process, such as the testing methodology and a reduction in investments derived. Thus, the 100€ /kWh stated in this thesis should be understood as the departing point of the 2nd life businesses, expecting lower prices in the following years. Moreover, car manufacturers will surely incorporate the 2nd life concept in future battery designs, such as an incorporated gateway or a 2nd life functional mode.

It can be also concluded that, in the nearby future, the SOH assessment won't be executed in laboratory conditions as it is done now. On the contrary, new methods to evaluate SOH during its 1st life in EVs using on-board data will be followed, such as the novel methodology presented in this thesis in Chapter 7. Consequently, it can be assumed that most of the information will be gathered by battery and communicated to the car owner, manufacturer or repurposing company just by connecting it to specific computation stations, as it is done now for ICEV diagnose in garages.

Regarding the RUL assessment, the first conclusion is that the electric equivalent circuit model is robust enough to provide trustable predictions; offering valuable information that could be used afterwards for further business calculations, such as amortization period, battery replacement maintenance and cost-profit analysis.

Additionally, the model showed that the RUL of reused batteries in most business models was longer than 5 years, being capable of achieving even more than 20 years in some cases, which is more than what actual lead acid batteries can offer. Moreover, as temperature of batteries on stationary applications is not expected to have dramatic changes or to go beyond 0 ^{o}C or over 30 ^{o}C, no cooling system should be installed. Even more, the refrigeration system that almost all EV and PHEV models include to control the battery temperature could also be neglected during the 2nd life. These results should enhance the use of Lithium reused batteries instead of new lead acid batteries on stationary applications.

The experimental results from cell aging tests presented two relevant findings. The first finding is that, between 70% and 40% SOH, the aging behavior might change somewhere, as two of the pre-aged cells tested presented faster aging than healthier cells. The second finding is that when these cells reach 40% SOH, aging seems to stabilize, which is most surprising as it goes against the sudden death effect that eventually occurs to all cells.

In addition, we should be very careful when talking about the EV, or the battery 2nd life from an environmental perspective. The EV and the battery reuse is beneficial only if it goes by the hand of RES. However, if energy storage systems should be used anyway, it clearly is better to reuse EV batteries instead of buying new batteries or other energy storage systems.

Finally, the last conclusion is that battery and car manufacturers are more interested in energy and power density improvements than in aging, which goes against the general environmental problem, as chapter 12 showed that the longer the lifespan of a battery, the lower its impact per kWh provided is.

13.1 Future works

Although EVs exist since the last century, it has not been until recently that they are becoming a serious promise. Its final entrance should be understood from environmental interests, the apparition of good performance Lithium batteries and financial incentives. Thus, the knowledge of aging beyond the 80% SOH is still not deeply studied. In fact, the aging tests results executed for this thesis, showed some astonishing results that should be further analyzed.

Additionally, the adapted 2nd life aging model showed that the aging behavior at low and high DOD and C-rates could not be completely assessed. The lack of more aging data relating the DOD and C-rate effects at their maximal and lower limits beyond the 80% SOH make it difficult to present contrasted enough equations. Thus, more tests should be carried out in this direction.

However, all these conclusion strongly depend on the SOH at the EoL in the vehicle. If new batteries improve their energy density to offer EVs with 400 km range or more, it is provable that the EoL in the vehicle is going to be delayed and the final SOH could go below the 70% or 60%. In this case the battery reuse would not be as interesting as with actual EV batteries, efficiency would have substantially decrease, the sudden death moment would be closer and functional failures are more provable to occur.

Thus, we have to wait and see which strategy car manufacturers finally select. The future of 2nd life of EV batteries strongly depends on less degrading materials or, from a practical perspective, the inclusion of 2nd life connectors, adapters, gateways or even a BMS prepared to communicate and manage batteries on stationary applications with more than one battery at the same time.

Furthermore, the improvements on recycling Li-ion battery processes have still an important role to play. If they can recover valuable materials at lower costs, recycling might become even more economically interesting than the battery reuse. So the battery reuse path on circular economy would lose strength and become a second or third priority for car manufacturers. However, their low price will still be sweetly enough for grid utilities and energy efficiency companies.

Another necessity that might boost the entrance and use of 2nd life batteries is perceived in the regulatory framework of the grid quality services, when regulation will fix this market, many business opportunities will appear.

Nonetheless, technology and economy are not the only issues that may enhance or complicate the battery 2nd life reality. Regulation and legislation are far from being up-to-date in this field. Some contacts and interviews occurred during these three years with local institutional administration for waste management. Right now, there is a substantial blank on how to identify these goods. Should they be considered as an industrial waste? Who'll be responsible of the battery at the end of the 2nd life? Should it be the car manufacturer? Or, by the re-selling contract, it falls directly to the re-purposing company? The answer to these and other questions is something that will be clarified within the following years as this activity becomes more and more frequent and regulations acknowledge it.

Additionally, in Spain, Li-ion batteries are yet not integrated in the regulations for low voltage installations. Thus, having no established security and installation's protocols, each time that these batteries are integrated in a system, excessive security measures are required by the security departments of the companies to reduce the uncertain risks of elements that they have never managed before. Evidently, this conservative attitude forces higher investments than what should be necessary. Once this step will be passed, everything will be clearer and, in consequence, budgets will lower and more accurate and investors will be eager to participate in.

However, batteries 2nd life businesses are called to overcome all these impediments as there are many actors willing for this to occur.

Research production

During this three years that lasted the research and writing of this thesis several scientific and research production was derived. All the articles, conference proceedings and posters done are chronologically listed below:

Ll. Canals, B. Amante, *An electric taxi fleet charged by second use batteries, not just economic profit*, W.J. of Science, Technology and Sustainable Development 10.3, 2013, pages 186-194. DOI 10.1108/WJSTSD-04-2013-0018

Ll. Canals Casals, B. Amante García. *An electric taxi fleet charging system using second life electric car batteries simulation and economical approach* CIO XVII, Valladolid. July 2013

Ll. Canals Casals, B. Amante García. M. Margarita González Benítez, *Segundas vidas para baterías de coches eléctricos: buenas ideas – malos negocios*, DYNA S.L., V.89, N.1 Feb. 2014, p.46-49. DOI: 10.6036/5763

Also published in the monograph Cuaderno DYNA nº 2: *Generación, Almacenaje y Distribución de la Energía*, December 2015, pages 41-44 DOI: 10.6036/CD2

B. Amante García, Ll. Canals Casals. *Evaluation of a pilot program that integrated generic and specific skills on engineering degree: a case study in Catalonia.* International journal of engineering education, Special Issue on "Engineering Education: Beyond Technical Skills", 2014, V.30.6, pages 1680-1688, DOI: 0949-149X/91.

Ll. Canals Casals, B. Amante García, *A review of the complexities of applying second life electric car batteries on energy businesses.* 1st Energy Systems Conference: When Theory Meets Reality. London, 23-24 June 2014.

Ll. Canals Casals, B. Amante García. M. Margarita González Benítez, *A cost analysis of electric vehicle batteries for second life businesses*, CIDIP, XVIII international congress on project management and engineering. Alcañiz, July 2014. Also published in the Lecture Notes in Management and Industrial Engineering book by Springer: *Project Management and Engineering Research, 2014*, pages 129-141, DOI 10.1007/978-3-319-26459-2.

Ll. Canals Casals, A. Schiffer González, *The Purposes of modeling electric vehicle batteries.* JIPI, Barcelona, 2015

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