Master's Thesis

Viability of Electric Vehicle Li-Ion Batteries for Stationary Storage Applications in the EU by 2030

under the guidance of

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Marc Diaz Caballo

Abstract

Electric vehicle batteries are not dead when they reach the end of their first useful life. Manufacturers are succeeding in bringing them back to life with three solutions: rehabilitating them, recycling them and, most importantly, reusing them in innovative applications that create significant value and encourage greater integration of renewable energy into grids. The introduction of these second-life batteries in households can lead to an improvement in energy efficiency and economic benefits for the user, as well as contributing to environmental care and sustainability.

Batteries from the first generations of electric vehicles are already being tested for various purposes around the world in order to extend the knowledge in this field and pave the way for building a reliable structure for future battery deployments. Therefore, numerous car manufacturers, together with energy companies and leading electronics companies, have in recent years carried out pilot projects of possible alternatives for the second-life of batteries.

To contribute to this study, this thesis presents an analysis to study the feasibility of deploying these second-life batteries in EU households to operate alongside the grid by 2030. The battery life prediction model provided in the article based on lithium batteries *Cycle-life model for graphite LiFePO4 cells*, as well as a study on the economic impact that these installations would have on users, has been necessary to obtain the preliminary findings on the economic viability. These results show a wide variety of outcomes, as they depend on household energy consumption and thus on life expectancy, which ranges from about 5 to 14 years.

Although the data are not very encouraging in general, a positive trend can be observed which may lead to an improvement of the situation in the coming years and make it feasible for each situation.

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Acronyms

Li-Ion	Lithium-Ion battery technology
EVs	Electric vehicles
GHG	Greenhouse gas
SoC	State of charge
SoH	State of health
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
ZLEV	Zero Level Emission Vehicle
ICE	Internal Combustion Engines
DoD	Battery's depth of discharge
C-Rate	Battery’s discharge rate
CEP	Cost equalization point

1. Introduction

1.1. Motivation

In recent years, electric and hybrid electric vehicles have attracted widespread interest worldwide. The main reasons for this demand are the concerns about the environmental impact of CO_2 emissions from internal combustion engine powered vehicles, improvements in battery technologies and the continuous rise in gasoline prices. Governments and manufacturers continue to make new commitments for electric vehicle sales, and the cost of manufacturing electric vehicles continues to fall, making them more affordable competitive with internal combustion vehicles. Furthermore, the European Commission has a target for achieving emissions-free transport by 2050 for passenger and commercial transport [1] and will largely depend on the continued transition to electric propulsion and will therefore require much greater battery production.

The high upfront cost of batteries for EVs is an important factor causing the reduction of the growth of the electromobility sector. Many manufacturers design their battery system end of life to be achieved after the batteries reach between 70% to 80% state of charge (SoC) which also creates an issue with rejecting many still usable batteries [2,3]. Approximately 95% of all lithium-ion batteries removed from electric and hybrid electric vehicles end up in a landfill [4], despite multiple requests from the industry of metal recycling companies. According to them, approximately 95% of the batteries deposited in landfills could be properly recycled or even used in other lower energy requirements applications.

Meanwhile, the increasing concern about the environment has also created a need to reduce the reliance on fossil fuels and grow the renewable energy production, such as wind and solar energy. However, due to the nature of these resources, wind and solar energy suffer from fluctuation in the output power, which negatively affects the stability and reliability of the grid. The most promising solution for this problem has been electrical energy storages, which again have the downside of the cost of the batteries [5]. In the same way that occurs in the electric vehicles, these batteries have a very high initial price. Being able to reuse the discarded batteries from electric vehicles to be used in stationary energy storage systems, we could reduce the costs of both electric vehicles and energy storage systems and thus extend the battery lifespan.

1.2. Objectives

1.2.1. Core objective

This thesis is an analysis examining the second-life electric vehicles batteries in stationary applications. The main objective of this work is to carry out a detailed study to evaluate the economic viability of introducing a system composed of second-life lithium-ion batteries in stationary storage applications. In the particular case of this work, this opportunity focuses on private residences, where second-life batteries can store a share of the electricity consumed by households to improve energy efficiency and bring economic benefits to users. Other reasons for considering the use of reconditioned batteries for stationary applications are the circular economy, environmental care and sustainability.

Three scenarios have been considered for the study of the economic feasibility of these installations with second-life batteries: European Union, Spain and Austria. The most general case is the European Union, which has been studied based on average energy usage values for all the countries that make it up, and allows us to obtain a global vision of the behaviour of the battery in both strategies presented. The other two scenarios go into greater detail by adopting average values for each country to observe the differences that are obtained with different electricity consumptions. The two previous mentioned situations are also considered in the two strategies of second-life battery use that will be presented in this paper.

1.2.2. Specific objectives

Furthermore, a series of objectives have been completed, as defined below, which have allowed the main objective to be achieved.

At the beginning of this work, a general review has been carried out of the different types of lithium-ion batteries that currently exist and which of them are mainly focused on electric vehicles. In addition to this initial study, some of the batteries implemented in the current EV models with the largest market presence have been compiled.

In order to give this project a solid meaning, it was necessary to confirm the economic viability of applications using second-life batteries as storage systems through real-life case studies. In the chapter that defines the state of the art, some of the most relevant projectors at European level are presented.

An analysis of the electromobility market to determine the volume of end-of-life battery stocks has also been carried out. This analysis defines the growth of the electric vehicle stock from 2010 to the present day and also presents two possible scenarios that could define its growth until 2030.

With all the information provided through the realisation of the previous targets and using the remaining useful life prediction model, it has been possible to approximate the possible economic savings and environmental benefits that these systems can offer by 2030. In order to observe the evolution of the investment cost and the reduction of CO_2 emissions, it has been compared with the values that would be obtained today using the same batteries.

1.3. Thesis structure

This study analyses the economic feasibility of using second-life batteries from electric vehicles for stationary applications in order to optimize electricity consumption in households in the European Union from 2030 onwards.

The first chapter introduces the current situation around electric vehicles and some of the reasons why they have become so popular in recent years. It also covers some of the negative consequences associated with the management of batteries once they are no longer useful in their first life period. This section also includes the objectives of this thesis.

The second segment goes into more detail on the state of the art involving lithium-ion battery technology, introducing its general operation and the different chemistries that are currently most commonly used. This section also includes a series of projects developed by car manufacturers and energy companies to understand the behaviour of second-life batteries in stationary applications and to analyse their viability.

The following chapters introduce a wide range of concepts that will be applied to the study of the feasibility of second-life batteries in domestic applications in the European Union, such as the evolution of the electric vehicle stock, household energy consumption or CO_2 emissions, and also present the two energy management strategies that will be studied in this project.

The sixth clause focuses on the methodology, which is the scientific procedure that is systematically applied during a research process to arrive at a theoretically valid result. This methodology is divided between the calculation procedure to obtain an approximation of the remaining useful life of second-life batteries and the calculation of the economic impact of the use of this technology.

The last sections gather all the results provided by the methodology, both in terms of remaining useful life prediction and economic impact, in order to be able to analyse the viability of each strategy in different situations and thus end the project with conclusions based on a solid foundation.

2. State of the art

Lithium-ion batteries play an important role in the life quality of modern society as the dominant technology for use in portable electronic devices such as mobile phones, tablets and laptops. Beyond this application lithium-ion batteries are the preferred option for the emerging electric vehicle sector, while still underexploited in power supply systems, especially in combination with photovoltaics and wind power. As a technological component, lithium-ion batteries present huge global potential towards energy sustainability and substantial reductions in carbon emissions [6]. This next chapter presents a detailed review of the state of the art regarding existing lithium-ion battery chemistries and the current projects being implemented, especially in Europe, with the use of second-life batteries.

2.1. Lithium-ion batteries

A lithium-ion (Li-ion) battery is an advanced battery technology that belongs to the family of rechargeable battery types, in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Chemistry, performance, cost and safety characteristics vary across lithium-ion battery types. Lithium-ion quickly became the battery of choice for most small electronics because it contained much higher energy density than comparable cells on the market. Meaning, you could create a battery with the same energy as NiMH[1] but it would be about half the size and half the weight [2]. For portable power applications such as laptops and cell phones, this meant longer run times and longer life batteries.

Lithium-ion batteries are comprised of an anode, cathode, separator and electrolyte. The basic working mechanism based on lithium-ion batteries is associated with the transfer of lithium ions from the positive electrode (cathode) to the negative one (anode) and vice versa. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The lithium ions move from the anode and pass through the electrolyte, often an organic solution of lithium salt such as $LiPF_6$ [7], until they reach the cathode and recombine with their electrons and electrically neutralize. The lithium ions are small enough to be able to move through a micro-permeable separator between the anode and cathode. The exact opposite occurs during charging as an external current is applied.

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[1] Nickel-metal hydride battery (NiMH) is a type of rechargeable battery commonly used in many laptop computers, as well in mobile phones, camcorders and other portable electronic devices.

2.1.1. Lithium-ion chemistries

Lithium-ion batteries can use a number of different materials as electrodes. The most common combination is lithium cobalt oxide (cathode) and graphite (anode), which is most commonly found in portable electronic devices such as cellphones and laptops. Some of the general performance characteristics of the most typical lithium-ion chemistries in use today are summarized below, including lithium cobalt oxide (LCO), nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA), lithium iron phosphate LFP), lithium titanate (LTO) and lithium manganese oxide (LMO) [8]. The battery manufacturer may use each of these six main chemicals, which are shown in Table 1, in different combinations to achieve different performance results, or in some cases the cell manufacturer may combine different chemistries to obtain the different benefits of each chemistry in a single cell design.

	Lithium Iron Phosphate	*Lithium Manganese Oxide*	*Lithium Titanate*	*Lithium Cobalt Oxide*	*Lithium Nickel Cobalt Aluminium Oxide*	*Lithium Nickel Manganese Cobalt Oxide*
Acronym	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy [Wh/kg]	80 - 130	105 - 120	70	120 - 150	80 - 220	140 - 180
Energy density [Wh/L]	220 - 250	250 - 265	130	250 - 450	210 - 600	325
Specific power [W/kg]	1400 - 2400	1000	750	600	1500 - 1900	500 - 3000
Power density [W/L]	4500	2000	1400	1200 - 3000	4000 - 5000	6500
Cell voltage [V]	3.2 - 3.3	3.8	2.2 - 2.3	3.6 - 3.8	3.6	3.6 - 3.7
Cycle life	1000 - 2000	> 500	> 4000	> 700	> 1000	1000 - 4000
Self-discharge (% per month)	< 1%	5%	2 - 10%	1 - 5%	2 - 10%	1%
Operating temperature range [°C]	-20 to 60	-20 to 60	-40 to 55	-20 to 60	-20 to 60	-20 to 55

Table 1. Lithium-ion chemistries [2].

Lithium-iron phosphate chemistry-based cells are the most widely used lithium-ion chemistry in automotive applications due to their exceptional properties. These cells have a high-power capability which allows them to accept a regenerative braking charge and provide a very fast acceleration discharge. In relation to some of the other scarce materials used in lithium-ion cells, iron phosphate is fairly common and therefore relatively less cost than other lithium-ion cell chemistries. Another reason the LFP has gained a high level of usage is that it has been recognized as a safer chemistry than the others. However, this is somewhat of an inaccuracy because all lithium-ion chemistries have similar failures. In this case, LFP has a lower energy density than the others, which means that there is less energy to discharge in the event of a failure [9].

2.2. Real-life applications of second-life battery storage systems in Europe

From a technical perspective, energy storage devices in complex systems have been widely studied and implemented in storage projects worldwide showing good performance and robustness [15, 32, 33]. Similarly, considering the specific case of the second-life EV batteries, major car manufacturers together with electricity utilities or power electronic companies launched several projects showing the capabilities of these reused batteries to offer residential, grid or renewable energy generation support among others [10].

This opportunity is gaining more and more importance worldwide and this is why several projects exist or are being launched that incorporate these second-life batteries. Below is a set of projects developed by automotive companies together with energy companies that incorporate an energy storage system composed of batteries (or battery modules in some cases) reused from both BEV and PHEV electric vehicles.

Less demanding applications than mobility, such as stationary uses, may constitute promising options to harvest the spared value of used EV batteries. In such applications, old batteries are expected to be able to provide services for about ten years more.

The first generations of used EV batteries are already being tested for various purposes around the globe, such as managing peak demand or regulating grid frequency [11]. This is because the first significant waves of electric vehicles for private use started to be sold in 2011 and, taking into account that the life of a battery lasts approximately 8 years in an electric vehicle [12], it is not yet possible to observe the results of their second use. This means that in recent years, only pilot models of possible alternatives for the second life of batteries have been seen, and therefore many of these batteries used for prototypes are of first use.

2.2.1. SUNBATT

Endesa[2] and SEAT joined forces with technology centres such as CIRCE4[3], the Energy Research Institute of Catalonia (IREC) and the Polytechnic University of Catalonia, under the SUNBATT project, which ended successfully in November 2016 [13]. The project has carried out a detailed analysis of the needs to adapt the batteries to second-life applications, as well as their behaviour during this new use. Within this analysis, the different applications in which they could be used have been studied, which could cover both domestic storage, distribution services in isolated areas of the grid, or its use in EV charging stations.

The SUNBATT laboratory, located on the premises of SEAT in Martorell, consists of a 15 square meter container within which the entire installation is located, composed of four batteries of electric vehicles from 8.8 to 24 kWh connected to a microgrid and two 20 kW bidirectional converters [14]. In addition to the batteries, the complete system includes some photovoltaic panels with 14 kW of generating power, three charging points for electric vehicles and connection to the electric distribution grid, as shown in Figure 1.

Figure 1. SUNBATT facility in SEAT Martorell. The inside of the SUNBATT container (left). EV chargers (right).

From CIRCE they emphasize that, thanks to SUNBATT, it has been shown that batteries from electric vehicles can play a new role outside of them, with estimated second-lifespan that would range from 6 to 30 years, depending on the application. Through the interfaces developed by SEAT, it has been possible to integrate batteries for electric and hybrid vehicles in an atypical environment for them, which combines the industrial field and the electricity grid itself. At the same time, a control software for the batteries has been developed which has been integrated as one more layer in the SUNBATT installation management program.

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[2] Endesa S. A., is a Spanish company in the electricity, gas and water sector, founded on November 18, 1944 under the name of Empresa Nacional de Electricidad S.A.

[3] The CIRCE foundation is a resources and energy consumption research centre.

2.2.2. PSA and Mitsubishi second-life project

EDF[4], Forsee Power[5], Mitsubishi Motors Corporation, Mitsubishi Corporation and PSA Peugeot Citroën announce to jointly study the possibility of the energy storage business in Europe utilizing used lithium-ion batteries from electric vehicles, and to launch the demonstration project installed in September 2015 in France at Forsee Power's new Headquarters near Paris, France [15].

The purpose of the project is to optimized smart grid and Energy Management System, combining solar, electric vehicles, stationary storage using new and reused batteries, in bi-directional mode. Figure 2 shows a diagram with all the elements involved in this installation.

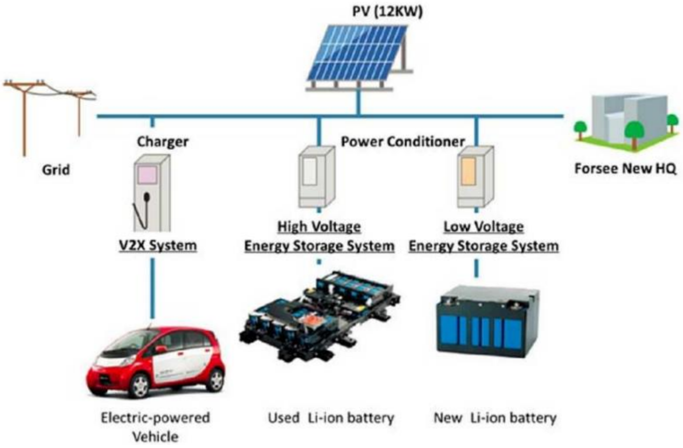

Figure 2. EDF, Forsee Power, Mitsubishi Motors Corporation, Mitsubishi Corporation and PSA Peugeot Citroën reused xEV batteries demonstration project schematic.

The system includes the following topics:

- ✓ High voltage (330 volts) Energy Storage System made of Peugeot Ion, Citroen C-Zero and Mitsubishi iMiEV reused automotive battery pack.
- ✓ Low voltage (48 Volts) Energy Storage System use of new automotive batteries.
- ✓ Capability of Electric Vehicle from Mitsubishi Motors "i-MiEV", Peugeot Ion, Citroen C-Zero and Plug In Hybrid EV Mitsubishi Outlander PHEV.
- ✓ Bi-direction battery energy consumption optimisation (car to building and building to car).
- ✓ Definition of a business model and its associated IP for the use of automotive batteries re-used in stationary applications.

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[4] Électricité de France or EDF is the main electricity generation and distribution company in France.

[5] Forsee Power is an industrial group specializing in smart battery systems for sustainable electric transport (LEV, trucks, buses, trains, marine vessels).

2.2.3. Battery 2nd Life project

BMW, Bosch and Vattenfall[6] are testing the use of second-life EV batteries in a 2 MW, 2.8 MWh energy storage system in Hamburg, Germany, to keep the electricity grid stable [15]. The electricity storage facility comprises 2,600 battery modules from more than 100 BMW's electric vehicles (ActiveE and i3 models). It could supply electricity to an average two-person household for seven months. However, the stored energy is not intended for general supply, but instead is sold on the primary control reserve market by Vattenfall, along with power from other flexibly controllable facilities. The storage facility delivers primary control reserve power necessary to keep the 50 Hz grid frequency stable. Primary control reserve power must be available within a few seconds.

The Battery 2nd Life development project organized by Vattenfall, BMW and Bosch kicked off in 2013 for a planned term of five years. The project would allow the three partners to gain new insights into potential areas of application for such batteries, their aging behavior and their storage capacity.

2.2.4. xStorage

The new xStorage project combines Nissan's expertise in vehicle design and reliable battery technology with Eaton's[7] leadership in power quality and electronics, resulting in a second life battery solution. The system contains second-life batteries from the Nissan Leaf, designed to enable customers to take advantage of time-of-use pricing and to provide back-up power. The system has also been designed with aesthetics and usability in mind to ensure it fits seamlessly into the home environment.

The domestic units will have a competitive starting price from € 3,500 (excluding VAT and installation costs) for a 3.5 kW capacity and rising to € 3,900 for a 6 kW capacity. Units powered by Nissan's new batteries will start at € 5,000 and go up to € 5,580 for the highest capacity, and will have an extended warranty period of ten years [15].

If a home is equipped with solar technology, consumers can power their homes using clean energy stored in their xStorage system, and be rewarded financially for doing so by avoiding expensive daytime energy tariffs. In addition, this installation can be found at the Johan Cruijff Arena (Amsterdam) where second-life Nissan Leaf batteries have been implemented to provide backup power with a total capacity of 3 MW [16].

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[6] Vattenfall is a European energy company that has been supplying energy to homes, businesses and industry for more than 100 years and modernising our way of life through innovation and cooperation.

[7] Eaton Corporation is an American multinational power management company.

3. Electric vehicle stock

The global electric vehicle market has taken a huge leap forward in the past decade due to several reasons of great importance, especially those of environmental origin. The transportation sector is one of the main reasons for global warming. About one-third of global energy demand and one-sixth of global greenhouse gas emissions (GHG) come from transport [17], mainly because of fossil fuels. In an attempt to solve this global issue, automotive manufacturers have been pushed towards the development of innovative technologies for the sustainable mobility of people and things making this rapid growth, that we are currently witnessing, possible. But even though we have already seen some incredible increase in the number of EVs worldwide, industry predictions would suggest that we have only just scratched the surface.

According to the Global EV Outlook of the Electric Vehicle Initiative (EVI) and the International Energy Association[8] (IEA), after a decade of quick rise, in 2020 the global electric car stock hit the 10 million mark, which means a 43% increase over 2019. Battery electric vehicles (BEVs) account for two-thirds of all electric vehicle types sold in the last decade.

China is the world's largest electric car market, with 4.5 million units and a growth of 34% compared to 2019. It is followed by Europe with 3.2 million units and an increase of 81% and the United States with 1.8 million units and a rise of 22%. The following Figure 3 defines the global development of the electric vehicle fleet over the last decade.

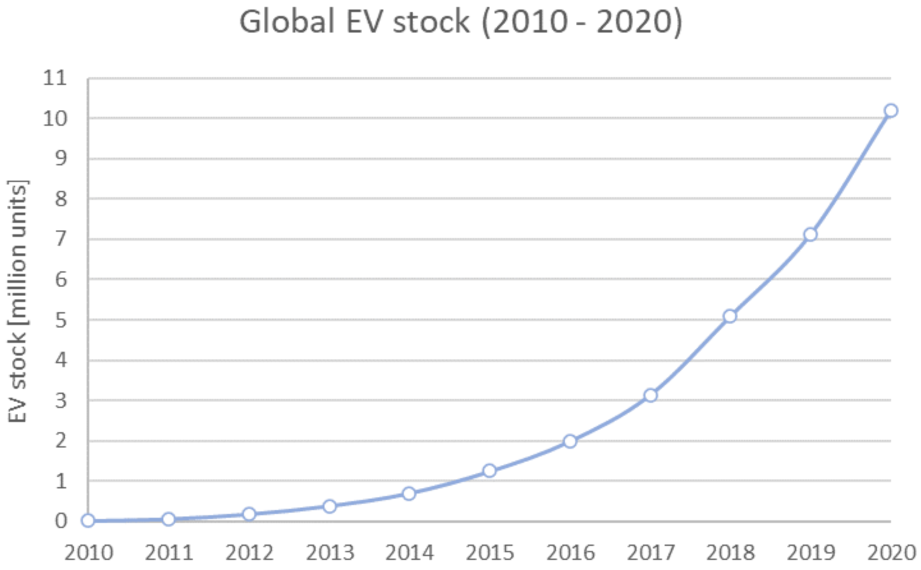

Figure 3. Global EV stock from 2010 to 2020 [18].

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[8] The International Energy Agency works with countries around the world to shape energy policies for a secure and sustainable future.

Overall, the global market for all types of cars was hit hard by the economic impact of the Covid-19 pandemic. In the first part of 2020, new car registrations fell by about one third compared to the previous year. This was partially offset by increased activity in the second half of the year, resulting in an overall decline of 16%. Particularly, with conventional and overall new car registrations falling, the share of global electric car sales increased by 70% to a record 4.6% in 2020.

A total of 3 million new electric cars were registered worldwide in 2020. In that year, Europe led the way with 1.4 million new vehicles, followed by China with 1.2 million and the United States with 295,000 new electric cars. This large number of registrations is closely related to numerous factors that were implemented during the automotive crisis in 2020 [19]. Electric cars are gradually becoming more competitive in some countries on a total cost of ownership basis. Several governments offered or extended tax incentives that cushioned electric car purchases in the face of falling car markets.

In reference to the European market, a very similar behavior is observed to the one previously presented with the global sales of electric vehicles. At the beginning of the last decade, the number of EV sales barely reached 10,000 units, with a larger presence of BEVs. It was not until 2012 that PHEVs began to gain prominence in the European market. As the years passed and the technology that encompasses the electric vehicle was improving and social consciousness became increasingly concerned about environmental problems, electric vehicles were gaining presence on European roads until reaching in 2020 the value presented above (3.2 million units). The Figure 4 represents this evolution which has been introduced previously.

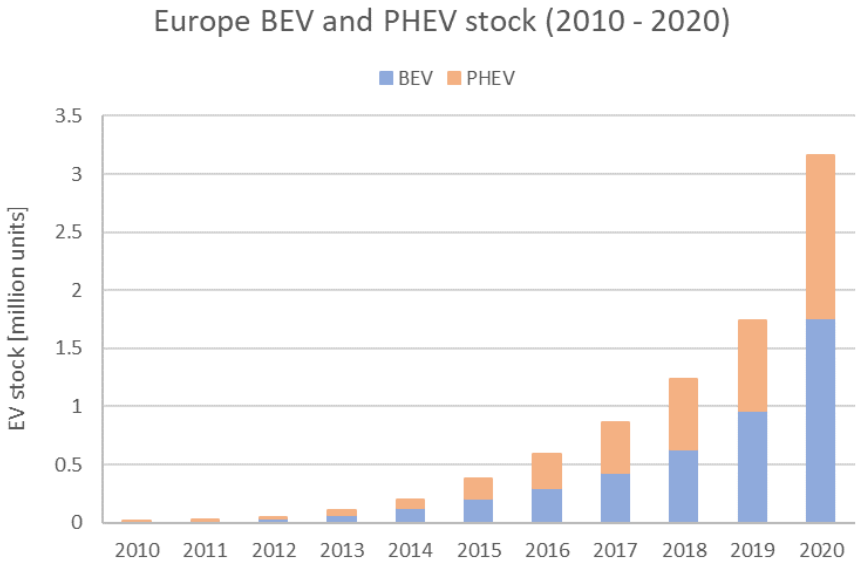

Figure 4. EV stock in Europe from 2010 to 2019 [18].

The uptake of electric vehicles in Europe is currently increasing rapidly, but it is still at an early stage. It is expected to accelerate through the mid-2020s. Forecasts indicate that by 2025 only 10% of total new vehicle sales in Europe will consist of zero and low emission vehicles[9] (ZLEV), this number is expected to increase to 25% in 2030. This would mean that in 2030 the remaining 75% of the vehicle stock will still be powered by internal combustion engines (ICE). However, by 2050 electric vehicles are expected to dominate the stock, reducing the proportion of ICE cars to 20% [20].

Due to the growth in the number of zero and low emission vehicles in the European market in the mid-2020s, the number of electric vehicles that will circulate on Europe's roads in 2030 will be close to 17.5 million, most of them relatively young and with a lifespan that could be extended. However, by 2030 it is expected to retire around 125,000 older electric vehicles and consequently recover their batteries. On the one hand, not all of these batteries will be available for being used in other second-life applications. Approximately 15% of these batteries would be too deteriorated for those applications and would be recycled, generating 2,800 tons of valuable metals. On the other hand, almost 105,000 EV batteries, representing around 2.25 GWh of residual capacity, would be repurposed in 2030. Those new batteries will be added to the roughly 250,000 EV already in use second-life applications before 2030 [20].

All the information extracted from the source [18] is collected in the Tables 15 and 16 in the annex. They show in detail the data used for the elaboration of the Figures 3 and 4 presented above.

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[9] ZLEVs refer to vehicles with emissions of less than 50g CO_2/km such as Plug-in Hybrid Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs).

4. Overview of household electricity use

The following section consists of a collection of relevant aspects concerning electricity use in the EU as well as providing important data for the calculations presented in the further sections.

4.1. Electricity usage in households

Households use energy for various purposes: space and water heating, space cooling, cooking, lighting and electrical appliances and other end-uses (mainly covering uses of energy by households outside the dwellings themselves). Data on household energy consumption in the 27 countries that make up the European Union, plus some additional data, have been collected and published by Eurostat [21].

The purpose of this section is to know what is the current average consumption of a European household and what will be its expected value in 2030, in order to proceed with the calculations of this project.

As a starting point for the study on the feasibility of second-life batteries, it is necessary to know the current average energy consumption of a European household. Figure 5 below shows the evolution of average European annual energy consumption per capita over the last 20 years.

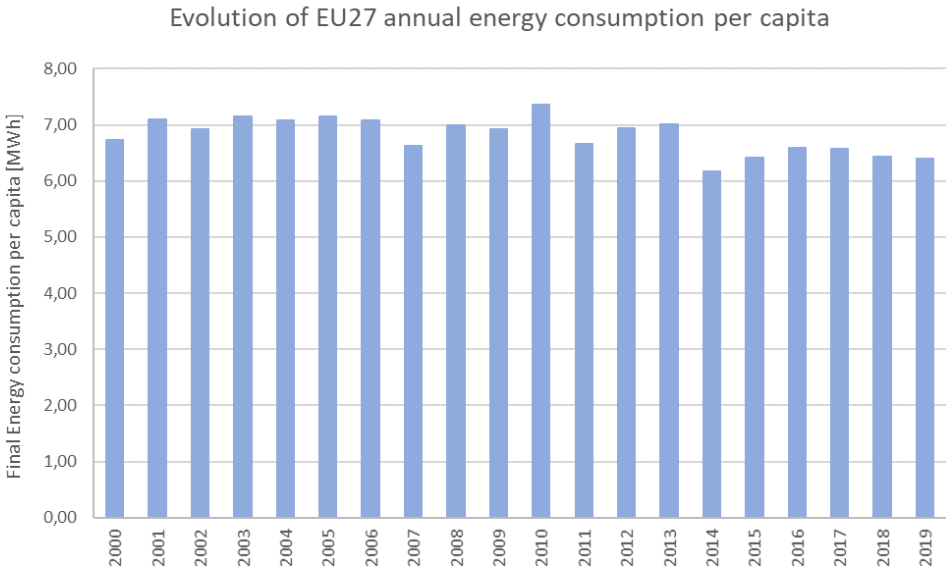

Figure 5. Final energy consumption in households per capita [21]. The indicator measures the amount of electricity each citizen consumes at home per year.

The same Eurostat publication contains information on daily energy consumption in 2019 for all the countries being part of the European Union. Figure 6 shows that difference and with other leading or former EU countries. The average European value of energy consumption in households is highlighted in orange and will be used to proceed with the necessary calculations.

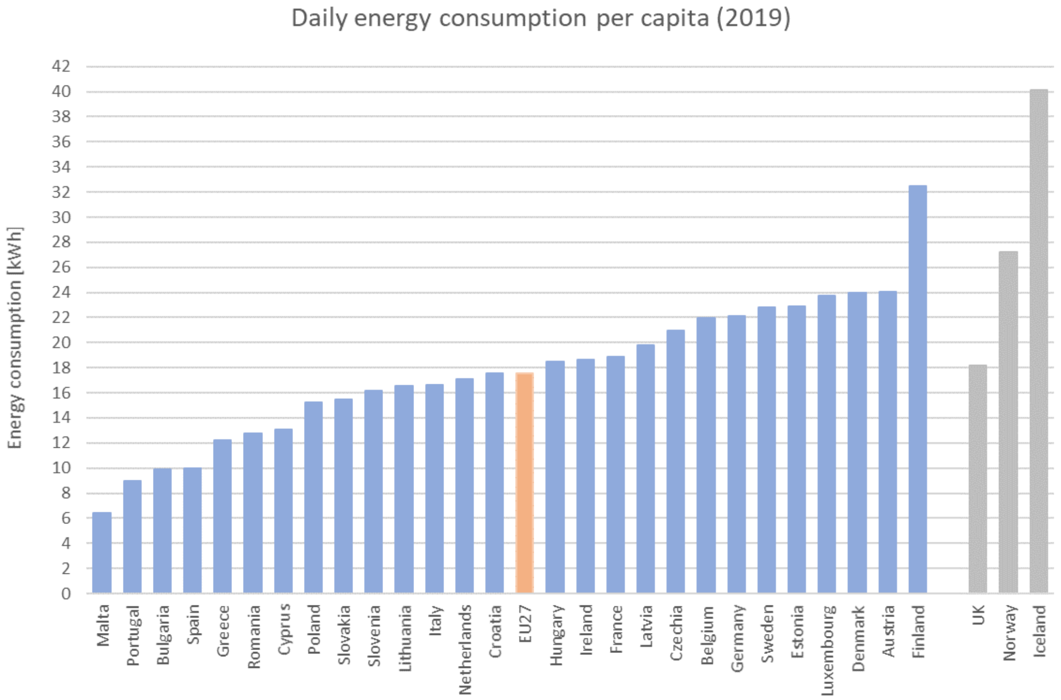

Figure 6. Daily electricity consumption per capita in 2019 [21].

From this study it has been possible to obtain the current average annual consumption, which is considered almost equal to that obtained in 2019, and the expected value for 2030. Based on the current value, the Figure 6 shows the value equivalent to 6.40 MWh per year. If we convert this value to energy consumed per day, in order to simplify the calculations, and assuming a constant consumption throughout the year, we obtain that the average daily consumption for a European household is 17.52 kWh (represented in orange in the graph above).

According to the U.S. Energy Information Administration[10], global residential energy consumption per capita is projected to increase by 0.6% per year until 2050 [22]. Based on this assumption, the expected average annual energy consumption for a European household in 2030 has been defined as 6.83 MWh. In the same way as in the previous case, if we reduce this energy consumption to a daily value, the energy consumed in 2030 per capita will be 18.72 kWh.

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[10] The U.S. Energy Information Administration (EIA) is a principal agency of the U.S. Federal Statistical System responsible for collecting, analysing, and disseminating energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment.

4.2. Daily consumption curve and electricity tariff

In order to carry out the study on the implementation of an energy storage system based on the use of second-life batteries to optimise energy consumption in households, it was necessary to establish the energy tariff and the daily electricity consumption curve.

The tariff chosen was the hourly discrimination tariff in electricity consumption, to simplify the calculations and to avoid having to consider more than one tariff.

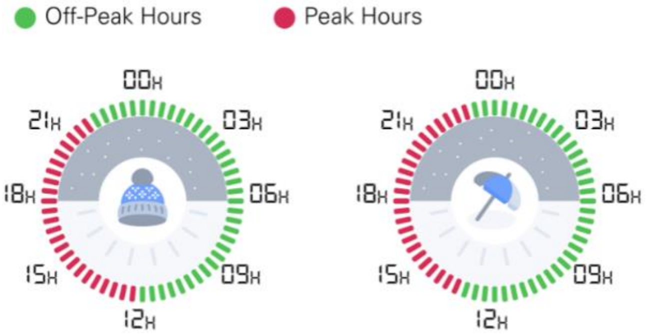

Figure 7. Hourly discrimination in electricity consumption [35].

The Figure 7 presented above, the electric company Endesa defines the periods of discrimination in energy consumption. The time-of-use rate is a billing alternative for your electricity consumption hours, in which there is a different price depending on the time of consumption. In other words, you will be charged one price or another depending on the time when you consume your energy.

These two-time windows are called peak and off-peak hours. On the one hand, 14-hour off-peak schedule runs from 10 p.m. to 12 p.m. in winter and from 11 p.m. to 1 p.m. in summer, and is the cheapest period for electricity. On the other hand, 10-hour peak schedule runs from 12 p.m. to 10 p.m. in winter and from 1 p.m. to 11 p.m. in summer, and is the most expensive period for electricity. Most of the hourly discrimination pricing schedules that exist on the market are restricted to these periods.

This tariff does not make any sense without a daily energy consumption curve showing the power consumed at each moment of the day. Based on the average consumption value of a European household, a value presented above and equal to 17.52 kWh, a daily energy consumption curve has been made which could show the actual energy consumption. In order to receive the appearance of the curve, the power variable had to be adjusted, so that the area under the curve is equal to the value of the daily energy consumed. In this way, the graph shown below has been acquired, which defines a general behavior for all the countries considered in the European Union.

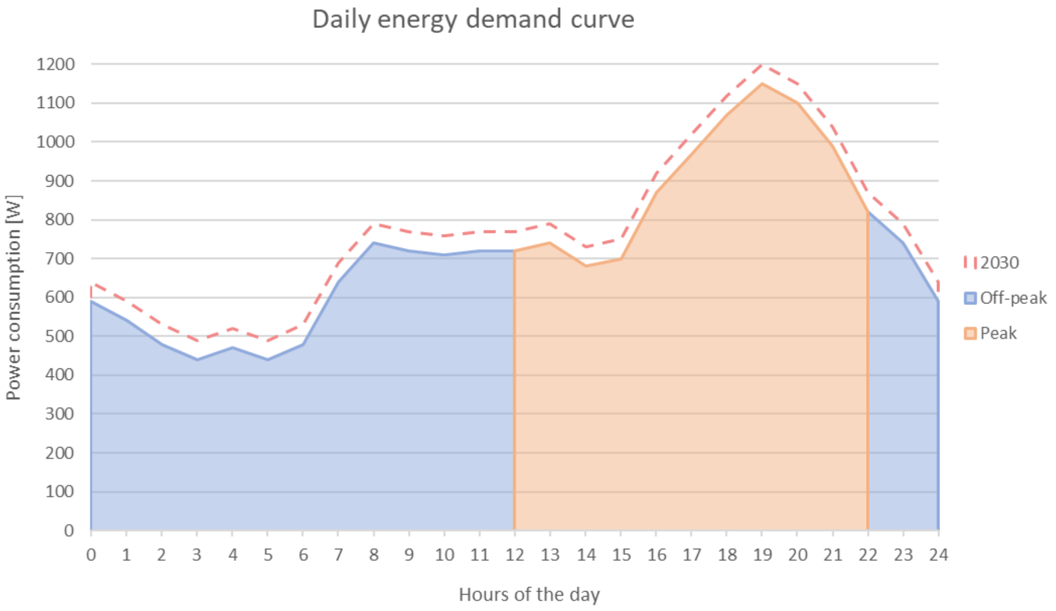

Figure 8. EU average daily energy demand curve. Own elaboration.

The energy demand presented above is divided into two regions marked by the colours blue and orange, which represent the energy consumed in off-peak and peak hours, respectively. The Figure 8 refers to the amount of energy currently consumed. Above the previously introduced curve, we can see what the energy demand for 2030 would be, the area under this new curve refers to the value of 18.72 kWh.

In both cases, the energy consumed during off-peak hours refers to 44% of the energy consumed throughout the day, therefore, the remaining 56% is energy consumed during peak hours, when the cost is higher.

	Daily EU average energy consumption [kWh]	*Off-peak hours energy consumption [kWh]*	*Peak hours energy consumption [kWh]*
Nowadays	17.52	7.71 (44%)	9.81 (56%)
2030	18.72	8.24 (44%)	10.48 (56%)

Table 2. Average daily energy consumption for a European household. Own elaboration.

The following section introduces energy optimisation strategies, that allow the second life batteries of electric vehicles to be used in energy storage systems during peak hours, in order to reduce the costs associated with household energy consumption.

4.3. CO_2 emissions from household energy generation

Over the past five years, the European Union has performed significant progress in promoting energy efficiency action, completing the internal market for electricity and gas, renewable energy deployment, greenhouse gas emissions reductions and a stronger carbon price signal. In 2019, the EU proposed the European Green Deal (EGD), a set of 50 actions for the coming five years across all sectors, to prepare the EU economy for climate neutrality by 2050 [23].

The European Environment Agency has assessed the CO_2 emissions intensity of the EU energy sector since the early 1990s [24]. The trend over time and how it has been decreasing due to the energy policies that have been implemented, is shown in the Figure 9 below.

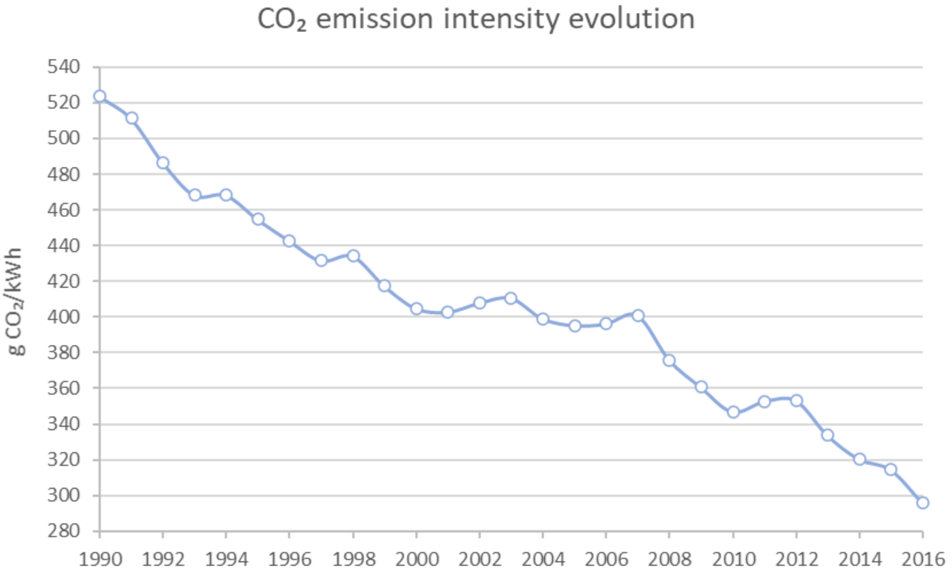

Figure 9. The CO_2 emission intensity (g CO_2/kWh) in the EU over the years since 1990 [24].

In order to obtain the value of CO_2 emissions due to current and expected energy generation in 2030, the decreasing trend has been considered to approximate these values. Considering this constant progression due to continued environmental policies, the current value is around 270 gCO_2/kWh and the expected value in 2030 drops to 208 gCO_2/kWh.

By international comparison, the EU has a significantly lower emissions intensity of power generation than other large economies. The carbon intensity was 290 grammes of CO_2 per kilowatt-hour (gCO_2/kWh) in 2018, compared with over 400 gCO_2/kWh in the United States, more than 500 gCO_2/kWh in Japan, around 600 gCO_2/kWh in the People's Republic of China and over 700 gCO_2/kWh in India and Australia.

Renewable energy sources such as wind, solar, hydro, ocean, geothermal, biomass and biofuels are alternatives to fossil fuels that help to reduce GHG emissions, diversify energy supply and reduce dependence on volatile and unreliable fossil fuel markets (in particular oil and gas). European legislation on the promotion of renewable energy has evolved significantly in recent years. EU leaders set a target of a 20% share of renewables in the EU's total energy consumption by 2020 in 2009, and in 2018 it has been agreed that, this target should be 32% by 2030. The future policy framework for the period beyond 2030 is under discussion [25].

This section will help to approximate the CO_2 emissions linked to different strategies on the use of second-life EV batteries in households as energy storage systems to optimise energy consumption.

5. Electricity consumption strategies with second-life batteries

These applications of second-life batteries are mainly focused on achieving a reduction in the cost of household electricity tariffs, taking advantage of batteries that are no longer useful in electric vehicles. To reduce the cost of the energy consumed, the aim of the batteries is to store the electrical energy extracted from the grid during off-peak hours or generated by solar panels, to be used during peak hours, when the price of electricity is higher.

There are several studies that date the remaining useful life for second-life batteries in electric vehicles depending on the application for which they are to be deployed. Results show that second-life battery lifespan clearly depends on its use, going from about 30 years in fast electric vehicle charge support applications, to around 6 years in area regulation grid services [14]. Other sources define that as a function of their condition, which is between 70% and 80% SoC, used EV batteries could deliver an additional 5 to 8 years of service in a secondary application [29].

5.1. Repurposed battery strategy recharged by the grid

The main objective of this application of second-use batteries is to reduce the cost of energy usage in households on a daily basis. To achieve this purpose, the mission of EV batteries is to store the energy extracted from the grid during off-peak hours to be used during peak hours, when the price of energy is higher.

This requires an AC/DC inverter capable of connecting the battery and the grid to allow electricity to flow in both directions, as shown in Figure 10.

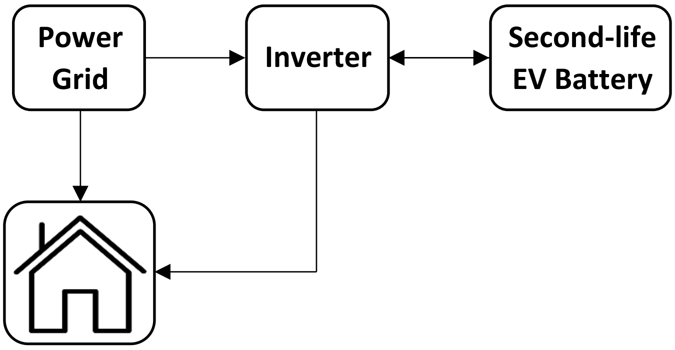

Figure 10. Diagram of the repurposed battery strategy recharged by the grid. Own elaboration.

In addition, it is necessary that the inverter has an EMS to be able to intelligently regulate the power supply or the moment in which the battery must store energy from the grid.

The EMS works through a working algorithm capable of calculating the moments of energy consumption with higher and lower prices and it is possible to visualize, through a software, these consumptions in order to be able to choose the sources, from which the energy is obtained for home at any given moment.

The benefit of this activity is expected to come from the difference in off-peak and peak energy prices, as the homeowner can analyse energy consumption trends and modify preferences for grid and battery consumption hours.

5.2. Repurposed battery to increase photovoltaic self-consumption

The objective of this second electricity consumption strategy with second-life batteries is also based on the same concepts as the previous one: to provide the necessary energy during peak hours thanks to a battery. Unlike the previous one, this battery is not charged by using the grid during off-peak hours. In this second case, solar panels come into play and are responsible for charging the battery during daylight hours.

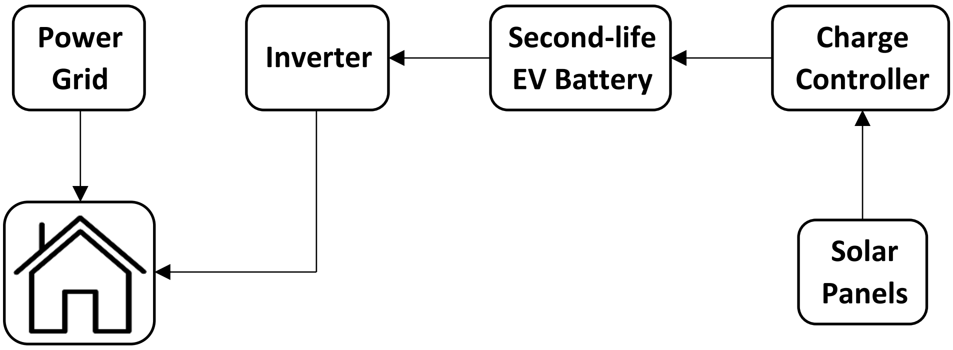

Figure 11. Diagram of the repurposed battery strategy to increase photovoltaic self-consumption in households. Own elaboration.

In this second strategy, the consumption of energy coming from the grid is much lower than in the previous one, contributing to the reduction of CO_2 emissions and the use of clean energy generation sources. However, as shown in Figure 11 above, this second strategy requires more elements to be installed, since it increases the costs of the installation. Both strategies offer advantages and disadvantages in certain aspects, but in the following chapters they will be evaluated economically to see which of them presents better opportunities and in which regions of the European Union they would be best used taking into account the climatic conditions.

5.3. Candidate batteries in energy optimisation strategies

This section lists some of the possible batteries that could be used in second-life applications from 2030 onwards. These batteries are being used in current electric vehicles and are expected to cease being functional as an energy storage system in vehicles by early 2030 and to be used in other applications with lower energy demand.

The list of batteries considered can be seen in Table 3, where they have been classified according to manufacturer, the model launch year, initial battery capacity, useful capacity of the battery and the nominal voltage provided by the battery.

Manufacturer	*Model*	*Year*	*Battery Initial Capacity [kWh]*	*Battery Usable Capacity [kWh]*	*Nominal Battery Voltage [V]*
Fiat	500e	2020	23.8	23.8	364
BMW	i3	2016 - 2017	33.2	27.2	360
Mini	Cooper SE	2020	32.6	28.9	350
Nissan	Leaf	2018	40	36	360
Hyundai	IONIQ	2016	40.4	38.3	360
VW	ID.3	2020	48	45	408
Tesla	Model 3	2019	55	50	350
Renault	ZOE	2019	54.7	52	400
Audi	e-tron 50	2018	71	64.7	396
BMW	iX3	2020	80	74	400

Table 3. Potential batteries that could be used from 2030 in second-life applications [34].

The batteries presented are in a wide range of capacities, as the electric vehicle is expected to have a noticeable increase in mobility both, for short distances within urban areas and for longer distances that require increased capacity.

Future batteries available for second-life applications will be suitable for different situations depending on the energy demand required by the application, creating a flexible market that can be adapted to multiple energy optimisation activities.

6. Method of approach

This chapter, divided into two sections, focuses on presenting the set of scientifically rigorous methods and techniques that are systematically applied during the research process to arrive at estimated results that will answer the hypothesis of the feasibility of using second-life batteries in stationary applications by 2030.

To proceed with this section, it has been divided into two subsections.

The first one is based on more technical concepts on the behavior and aging of lithium batteries reflected in the article based on lithium batteries *Cycle-life model for graphite LiFePO4 cells* [28]. This subsection will present the remaining battery life prediction model defined in chapter 5.3 above, focusing on the Tesla model 3 battery, and taking into account several variables that directly affect the longevity of the batteries such as cycling time, working temperature, depth of discharge and rate of discharge during the cycle. This prediction model aims to study the aging of batteries throughout their use in second-life applications in residential properties using the two strategies defined in the previous chapter, estimating their remaining useful life (in years), which will be useful to confirm their viability in the following subsection.

The second subsection will focus on the economic study on the feasibility of using second-life batteries in stationary applications by 2030. This means that, for these applications to be viable, the price associated with them should be lower than the price associated with electricity consumption using only the grid. Due to the initial investment required for these installations, this viability will not be achieved until a few years later. This section aims to show the evolution of the total price associated with electricity consumption with and without second-life battery and to estimate the point where both costs are equal, which is defined as the cost equalization point (CEP).

For the case of the installation with a second-life battery, two possible scenarios have been considered, referring to the two battery charging configurations:

- A second life battery system charged by grid power during off-peak hours.
- A second life battery system charged by photovoltaic panels.

An important aspect to take into account is that in all the cases studied a two-period time discriminating tariff and an energy consumption curve as presented in chapter 4 are considered.

This section only includes the equations for the approximate calculation of the cost associated with the two scenarios, with and without battery, which will be presented later in the results.

6.1. Battery aging model

Similarly to other battery chemistries, EV battery degradation occurs along time and use, in other words, losing capacity and power when they are in use or in a stand-by mode [26]. In particular, it is considered that these batteries are no longer useful for traction purposes when they have lost between 20% to 30% of their initial available capacity (after 8 to 12 years in a vehicle) [27], where capacity refers to the amount of amperes per hour (Ah) that a battery can deliver in a cycle. To determine the life of reused batteries in their second life application, the calculation procedure defined in the article based on lithium batteries [28] has been followed as well as taking into account the following factors or parameters:

- Cycling time (t)
- Working temperature (T)
- Depth of discharge (DoD)
- Discharge rate during cycle (C)

Therefore, the percentage of capacity loss (Cap_{loss}) produced in the battery can be determine based on the above parameters:

$$\mathrm{Cap_{loss}} = \mathrm{f}\,(\mathrm{t}, \mathrm{T}, \mathrm{DoD}, \mathrm{C}) \tag{1}$$

6.1.1. Depth of discharge effect

Cells cycled at DoDs greater than 50% reach the defined end of life condition sooner than those cycled at lower DoDs (<50%). This behaviour can be observed in Figure 12, where the percentage of capacity loss is represented as a function of the number of cycles for different DoDs.

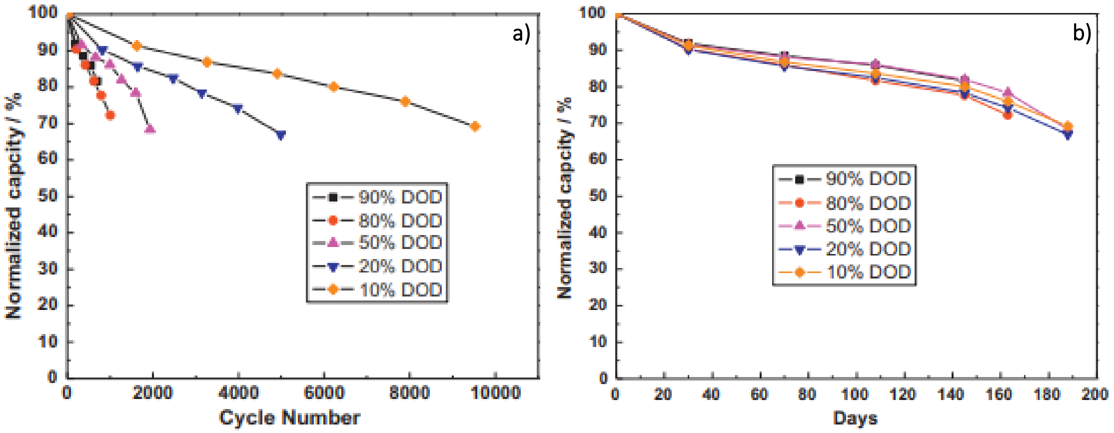

Figure 12. Capacity retention plotted as a function of a) cycle number b) time (days) [28].

However, when the same data is plotted as a function of time as shown in Figure 3, the results indicate DoD has very little effect on capacity fade. Therefore, the DoD effect was not considered to determine the capacity losses behaviour. After removing the DoD, the capacity fading can only be affected by cycling time (t), working temperature (T) and discharge rate (C).

$$\mathrm{Cap_{loss}} = \mathrm{f}\,(\mathrm{t}, \mathrm{T}, \mathrm{C}) \tag{2}$$

6.1.2. Cycling time and working temperature effect

The working temperature is one of the most important factors to take into account for remaining life cycles in batteries. The higher the working temperature is, the faster the chemical reaction will occur. This often translates to an increase in performance but, for the case study, it corresponds also to a loss of battery life as unwanted chemicals reactions occur and, at the same time, the battery capacity fades sooner.

Based on the Arrhenius equation and using the model proposed in article [28] to calculate battery capacity losses, we obtain:

$$\mathrm{Cap_{loss}} = \mathrm{B} \cdot \exp\left[\frac{-\mathrm{E_a}}{\mathrm{R \cdot T}}\right] \cdot \mathrm{t^z} \tag{3}$$

Where:

- $\mathrm{Cap_{loss}}$, percentage of capacity loss [%]
- B, pre-exponential factor
- $\mathrm{E_a}$, activation energy [$\mathrm{J \cdot mol^{-1}}$]
- R, gas constant in [$\mathrm{J \cdot K^{-1} \cdot mol^{-1}}$]
- T, absolute temperature [K]
- t, cycling time [s]
- z, power law factor

Moreover, since the amperes per hour (Ah) are proportional to time, it is possible to substitute them in the previous equation 3. This change serves to be able to correlate the Ah with the discharge rate taking into account that the repurposed batteries will be working continuously.

$$\mathrm{Cap_{loss}} = \mathrm{B} \cdot \exp\left[\frac{-\mathrm{E_a}}{\mathrm{R \cdot T}}\right] \cdot \mathrm{Ah^z} \tag{4}$$

$$\mathrm{Ah} = \mathrm{cy} \cdot \mathrm{D} \cdot \mathrm{Cap_{max}} \tag{5}$$

Where:

- Ah, amount of charge delivered by the battery during cycling [Ah]
- cy, battery cycles (charge and discharge)
- D, Depth of discharge [%]
- Cap_{max}, percentage of maximum capacity the battery can discharge [%]

6.1.3. Discharge rate effect

Finally, to determine the effect of the discharge rate C it is necessary to add the parameter to the equation that allows the capacity losses to be calculated. For higher C rates and low B parameters, the loss of capacity is more noticeable in batteries than for low C rates and high B parameters and, therefore, it is necessary to take this parameter into consideration, despite the fact that the two most influential parameters for the calculations are time (or Ah) and working temperature.

$$\mathrm{Cap_{loss}} = \mathrm{B} \cdot \exp\left[\frac{-31{,}700+370.3\cdot \mathrm{C}}{\mathrm{R}\cdot \mathrm{T}}\right] \cdot \mathrm{Ah}^{0.55} \tag{6}$$

Where:

- C, discharge rate [h^{-1}]

On the one hand, based on the model of article [28], the equation 6 used to determine the repurposed batteries lifespan in stationary applications is presented. On the other hand, to predict the pre-exponential factor B, the logarithmic regression of the results obtained for different discharge rates extracted from the same article [28], is shown in the following Table 4.

C-rate	*pre-exponential factor B*
C/2	30330
2C	19300
6C	12000
10C	11500

Table 4. Pre-exponential factor B values as a function of the C-rates [28].

Once the experimental points are known, a logarithmic regression line can be plotted to estimate the value of the other experimental points for other C-rates.

The following Figure 13 shows the mathematical expression used to estimate the values of factor B for the desired C-rate values.

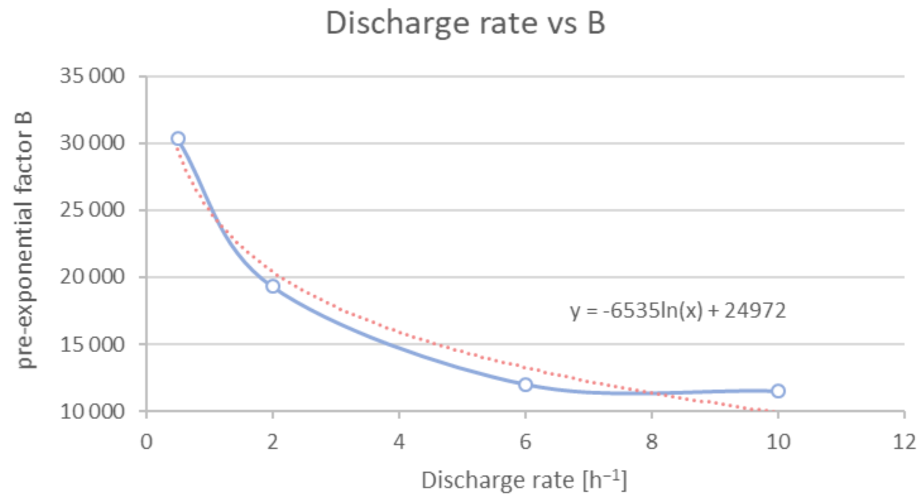

Figure 13. Relation between discharge rate and pre-exponential factor. Own elaboration.

By isolating the variable cycles from equation 6, the following expression is obtained and will be used in the next section to estimate the remaining cycles of the second-life batteries.

$$cy = \frac{\sqrt[0.55]{\frac{\mathrm{Cap_{loss}}}{\mathrm{B\cdot exp}\left[\frac{-31{,}700+370.3\cdot \mathrm{C}}{\mathrm{R\cdot T}}\right]}}}{D\cdot \mathrm{Cap_{max}}} \qquad (7)$$

6.2. Economic model

As previously introduced, this section includes the equations that will be used to obtain the accumulated costs over a certain period of years of electricity consumption per user, taking into account whether or not an installation has been made with second-life batteries.

The two equations that allow us to estimate the cost are the following:

C_{wrb}, Cost with repurposed batteries [€]:

$$C_{wrb} = i + T \cdot p \cdot d \cdot t + T_o \cdot e_o \cdot d \cdot t \quad (8)$$

C_{worb}, Cost without repurposed batteries [€]:

$$C_{worb} = T \cdot p \cdot d \cdot t + T_o \cdot e_o \cdot d \cdot t + T_p \cdot e_p \cdot d \cdot t \quad (9)$$

Where each term represents the following variables:

- i, initial investment cost [€]
- p, power contracted [kW]
- e_p, energy taken from the grid during peak hours [kWh]
- e_o, energy taken from the grid during off-peak hours [kWh]
- d, days of the year (assuming a constant value of 365)
- t, years
- T, daily power term [€/kW]
- T_p, energy term during peak hours [€/kWh]
- T_o, energy term during off-peak hours [€/kWh]

Concerning the initial investment, this is composed of the second-life battery and the additional components for the operation of the installation, shown in Figures 10 and 11. Table 17 in the appendix shows the associated costs for each battery based on the currently known costs per kWh [€/kWh]. The current price per kWh is within the range of \$75 to \$100 [30,31], while the estimated price per kwh for 2030 will be close to \$40 [20].

Once all the results are available, they will allow us to see if the investment to be made would be profitable. This means, if the remaining useful life of the battery, which we will obtain in the results section of the battery aging model, would be higher than the cost equalization point obtained in the results section of the economic study.

7. Results

The following chapter presents the results calculated using the model proposed in article [28], analysing the two scenarios defined above.

The numerical results presented are based on the Tesla Model 3 Standard Range Plus 55 kWh battery. Due to the great popularity in sales of this electric vehicle model, it has been decided to proceed with its detailed study since it is assumed, that at the end of its first useful life, a large amount of these batteries will be destined to second life applications.

Contrasting the results that would be obtained in 2030, according to current forecasts, it was decided to compare the economic impact of the same battery for the same stationary application if it was implemented today.

7.1. Battery aging model results

7.1.1. Initial conditions of the repurposed battery

The nominal capacity of the Tesla Model 3 battery at the beginning of its life is 55 kWh. From this capacity, 5 kWh of inactive capacity must be deducted to get the actual capacity intended to power the electric vehicle. This remaining 50 kWh represents 100% state of charge and 90.91% of the battery's state of health.

Table 5 shows the range of remaining capacity values of the Tesla Model 3 battery, depending on the SoC at the end of the first battery life in the vehicle, taking into account that at the beginning of the vehicle life with a 100% SoC, the capacity value is 55kWh.

SoC [%]	*Capacity [kWh]*
80	40
75	**37.5**
70	35

Table 5. Remaining Tesla Model 5 battery capacity calculated based on the battery's remaining its state of charge. Own elaboration.

In line with the introductory section, the end of life of an electric vehicle battery is reached when the battery reaches a state of charge of between 70% and 80%. The table above shows the remaining battery capacity values, depending on the state of charge of the battery at the end of its first lifetime. The average value of 75% SoC has been highlighted as it will be the average value considered for the initial calculation process on the viability of these batteries in the two energy optimisation strategies presented above.

7.1.2. Depth of discharge

The depth of discharge (DoD) is the fraction or percentage of the capacity that has been removed from the fully charged battery. In order to determine this value, it is necessary to recall the daily energy consumptions for an average European household today and in 2030 as presented in Table 6.

	Daily EU average energy consumption [kWh]	*Off-peak hours energy consumption [kWh]*	*Peak hours energy consumption [kWh]*	*Energy in battery [kWh]*
Now	17.52	7.71	9.81	11.01
2030	18.72	8.24	10.48	11.77

Table 6. Average daily energy consumption of a European household and the energy required to be stored in the battery. Own elaboration.

If it is considered that this consumption remains constant during the whole time this battery is used in the second-life application, the depth of discharge can be calculated, which will later be used to obtain its useful life.

	nowadays	*2030*
Second-life initial available capacity [kWh]	37.5	37.5
Second-life capacity after discharge process [kWh]	26.49	25.73
DoD [%]	29.37	31.38

Table 7. Depth of discharge today and in 2030 calculated on the basis of the capacity that the battery must provide. Own elaboration.

As introduced above, it is considered that the average electricity consumption during peak hours would be 11.01 kWh today and 11.77 kWh from 2030 onwards. Subtracting from the initial value of 37.5 kWh the amount of electrical energy that it should provide during those same peak hours gives the remaining capacity values after discharge. If we divide these two values according to the following formula, we can obtain the DoD expressed in Table 7 above.

$$\mathrm{DoD}\ [\%] = 100 - \left(\frac{\mathrm{Cap_f}}{\mathrm{Cap_i}}\right) \cdot 100 \qquad (10)$$

Where:

- $\mathrm{Cap_i}$, Second-life initial available capacity [kWh]
- $\mathrm{Cap_f}$, Second-life capacity after discharge process [kWh]

Figure 14 below shows the charge and discharge cycles to be performed during a week, where the energy consumption is kept constant and the battery is charged to full charge (under second-life conditions) during off-peak hours.

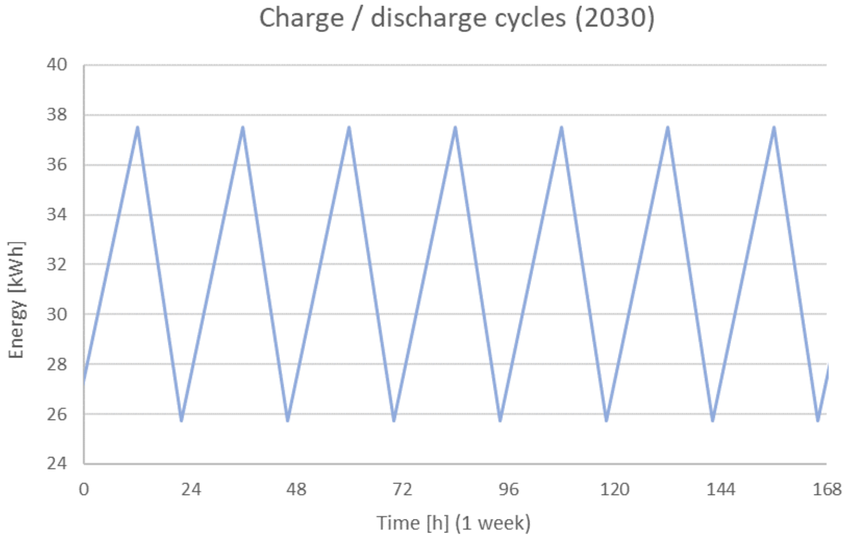

Figure 14. Charge and discharge cycles in 2030. Own elaboration.

The behaviour observed in the above figure does not remain constant over time. As introduced in the battery aging model, as the battery is used, there is a progressive loss of capacity until the point is reached where the battery is no longer able to supply the necessary energy. The length of time the batteries will last is calculated precisely by determining the maximum capacity loss that the battery can have to continue to perform its function and, assuming in the best-case scenario that the battery can lose capacity to provide the amount of energy needed during peak hours.

Figure 15 represents the evolution of the capacity loss over time since the beginning of the electric vehicle battery's second life, expressed in years, and how this loss affects the amount of energy the battery can store. The end of battery life is reached, when the battery is no longer able to supply the required amount of energy, equal to 11.77 kWh (introduced in Table 6).

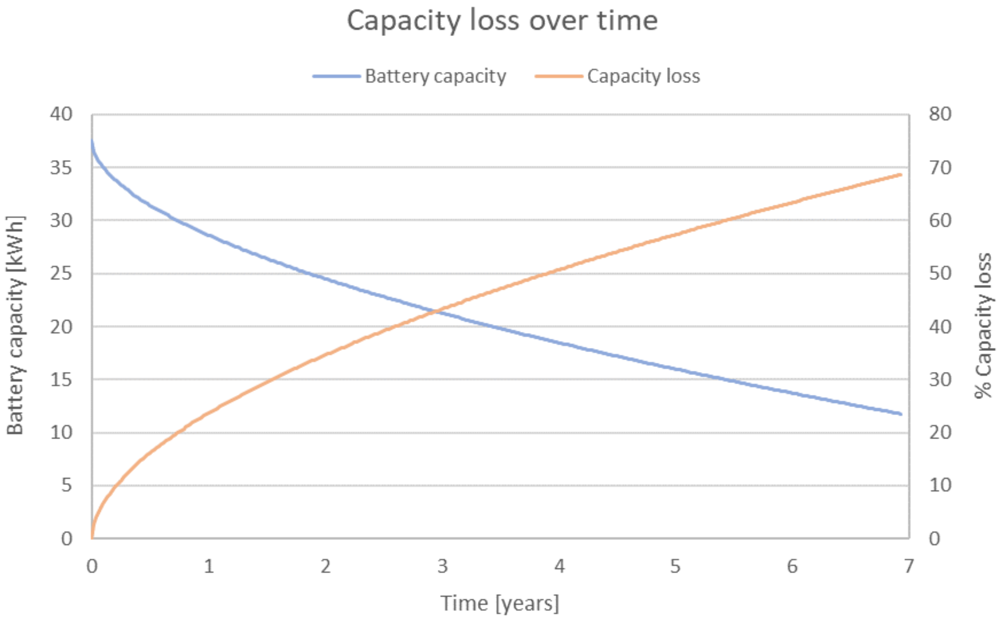

Figure 15. Capacity loss [%], as a function of time, of the Tesla Model 3 battery from the beginning of its second battery life in stationary applications represented in orange. Remaining capacity [kWh] of the same battery after capacity loss represented in blue. Own elaboration.

The capacity loss values have been obtained from equation 7. In this case, the percentage capacity loss variable (Cap_{loss}) was isolated from the equation and the battery was considered to have a continuous use without interruption and performing a complete daily cycle (charge half-cycle plus discharge half-cycle).

$$\mathrm{Cap_{loss}} = (\mathrm{cy} \cdot \mathrm{D} \cdot \mathrm{Cap_{max}})^{0{,}55} \cdot \mathrm{B} \cdot \exp\left[\frac{-31{,}700+370.3 \cdot \mathrm{C}}{\mathrm{R} \cdot \mathrm{T}}\right] \tag{11}$$

Taking into account the decreasing capacity of the battery over time and the energy consumption during peak hours, the following Figure 16 represents what the charge and discharge cycles would look like at different times during the lifetime of the battery.

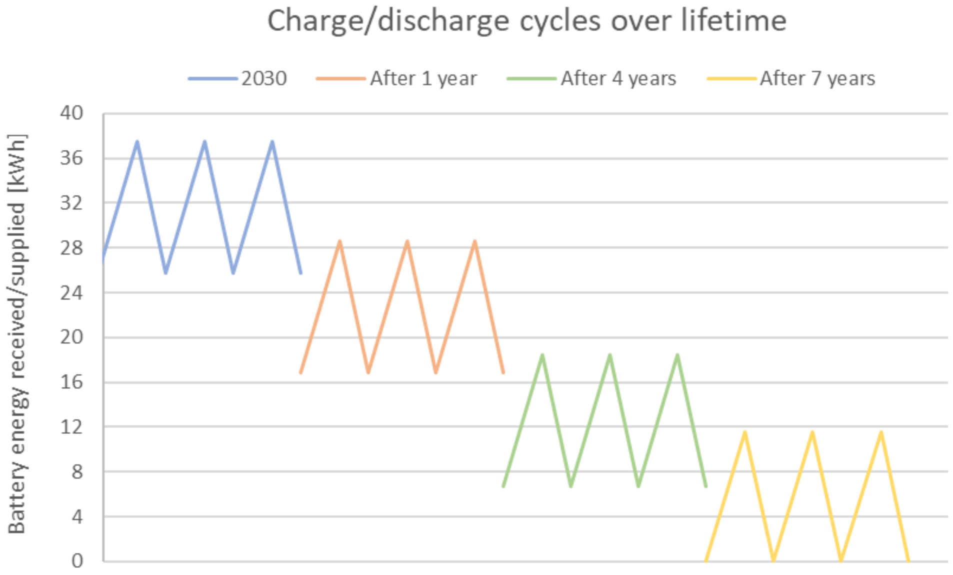

Figure 16. Time-dependent charge and discharge cycles, with a start date in 2030. Own elaboration.

The charge and discharge cycles represented in blue coincide with the cycles presented in Figure 14, which only occur in the early stages of the battery's life. As the battery loses capacity, these cycles are positioned as shown in Figure 16. The point, at which the battery ceases to be functional, coincides with the point at which the maximum capacity of the battery matches the energy it should provide and therefore the battery is fully discharged.

7.1.3. Lifespan

The following is the most relevant aspect that will allow us to know the viability of this application. Using equation 7 defined above, we can know the remaining useful life of this battery under different parameters.

The following Figure 17 shows, how battery life varies as a function of operating temperature. In order to receive the results, a constant temperature equal to 25°C has been considered. The useful life that would be obtained today, under the previously defined working conditions, would be 2793 cycles (7.65 years) compared to the 2521 cycles (6.91 years) expected in 2030. This slight difference is mainly related to the increase in energy consumption by 2030 and, consequently, the increase in the depth of discharge.

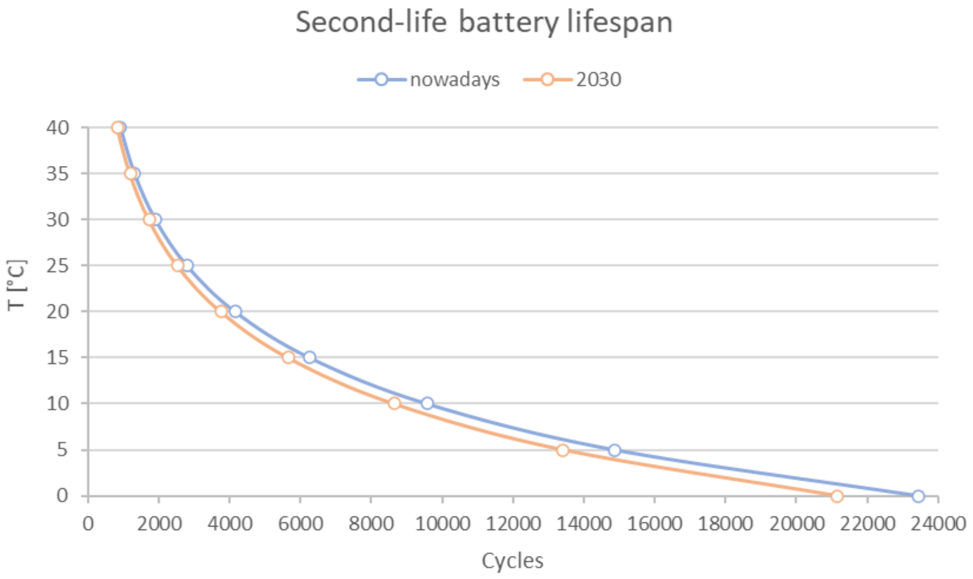

Figure 17. Expected useful life nowadays and in 2030. Own elaboration.

The values used in Figure 17 above are shown below. As introduced above, the values of the remaining cycles have been calculated using equation 7, keeping all the other variables constant and only modifying the values of the temperature.

T [°C]	*T [K]*	*2020*		*2030*	
		Cycles	*Years*	*Cycles*	*Years*
0	273.15	30764	84	28347	78
5	278.15	19497	53	17966	49
10	283.15	12557	34	11571	32
15	288.15	8212	22	7567	21
20	293.15	5448	15	5021	14
25	**298.15**	**3665**	**10**	**3377**	**9**
30	303.15	2498	7	2302	6
35	308.15	1724	5	1588	4
40	313.15	1204	3	1109	3

Table 8. Values calculated using equation 7 for the expected useful life now and in 2030. Own elaboration.

These results confirm the statement made in the previous section 6.1.2. where temperature was defined as one of the most important factors to take into account when estimating the remaining life cycles of the batteries. It is confirmed that the higher the working temperature, the faster the chemical reaction will be, and therefore a loss of battery life is accelerated and the battery capacity fades earlier.

7.1.4. Other batteries results

This section presents a prediction of the remaining lifetime that the following batteries would have in second-life applications in 2030 according to the presented model.

This group of batteries is presented in the following Table 9 in order from lowest to highest capacity. As already introduced at the beginning of this work, batteries in EVs are no longer functional when they reach a state between 70% and 80% SoC. Table 9 shows the range of capacities and, consequently, the range of useful life depending on the state of charge of the battery in use.

Manufacturer	*Model*	*2L Battery capacity [kWh]*		*Remaining useful life [years]*	
		70% SoC	*80% SoC*	*70% SoC*	*80% SoC*
Fiat	500e	16.66	19.04	1.88	2.93
BMW	i3	19.04	21.76	2.90	3.92
Mini	Cooper SE	20.23	23.12	3.28	4.24
Nissan	Leaf	25.20	28.80	4.95	5.78
Hyundai	IONIQ	26.81	30.64	5.35	6.13
VW	ID.3	31.50	36.00	7.12	7.85
Tesla	**Model 3**	**35.00**	**40.00**	**6.61**	**7.16**
Renault	ZOE	36.40	41.60	7.75	8.34
Audi	e-tron 50	45.29	51.76	8.57	8.98
BMW	iX3	51.80	59.20	9.08	9.40

Table 9. Table showing the range of values over the initial capacity in the second life and the remaining lifetime depending on the SoC limits. Own elaboration.

These values are represented in the following Figure 18, which shows more clearly how the remaining capacity of the battery influences its useful life in second-life applications.

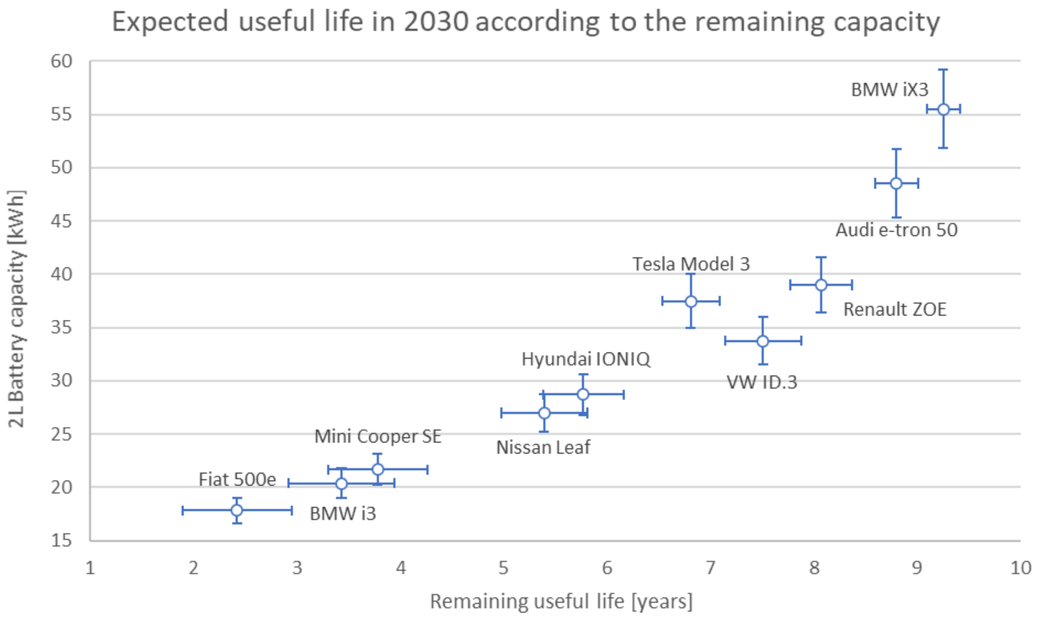

Figure 18. Graph representing the values in table 9. Own elaboration.

7.2. Economic model results

The economic study will be in charge of justifying if the application, for which the second life battery is intended, is profitable taking into account its useful life.

In order to observe more clearly the positive trend that shows, as years go by, these applications become more profitable. The cost equalization point that would be obtained, if today the Model 3 battery was used for a stationary application has been compared, with the cost equalization point that would be achieved, if the exact same battery that would be implemented in the same application in the year 2030.

Regarding the economic characteristics, one of the most important values is the difference in price between the energy consumed at peak and off-peak hours, since the greater the difference, the more benefit can be received from the application. Table 10 below shows average values obtained after observing different electricity tariffs in some European Union countries, of which Spain stands out. In this country, the leading company in the energy sector is Endesa, and the values of the power and energy terms have had a considerable weight in obtaining these average values [35].

It should be taken into account that for an average household the contracted power is 4.6 kW and with the use of batteries, the contracted power can be the minimum of 2.3 kW.

Electricity rate	*Power term [daily €/kW]*	*Energy term [€/kWh]*	
		Peak	Off-peak
Rate 2.0DHA (time discrimination) general power ≤10kW	0.1042	0.150	0.087

Table 10. Average prices considered for the power and energy term for an hourly discrimination tariff. Own elaboration.

Another aspect to consider, is the kWh price of second-life batteries that currently exists and is expected to exist in 2030. This is a fundamental factor, that will allow these applications to become increasingly profitable, due to the continuous reduction in the price per remaining kWh. Currently, the price per kwh is between $ 75 and $ 100 [30,31] while the expected price per kwh in 2030 will be close to $ 40 [20].

7.2.1. Repurposed battery strategy recharged by the grid

The necessary elements to be added to the installation are summarized in Table 11.

	Price today [€]	*Price in 2030 [€]*	*Efficiency [%]*
Tesla Model 3 repurposed battery	2716	1253	90
Inverter	≈1600	≈1200	99

Table 11. Initial investment for reused battery strategy recharged by the grid [36].

The price of the inverter, as well as that of the battery, is expected to be reduced since there are no proposals today that are specifically adapted for the proposed activity.

The results can be seen in Figures 19 and 20 below, which refer to the cost equalization point predicted by 2030 and nowadays. The values represented in the following graphs have been calculated using equations 8 and 9 from chapter 6.2, which respectively refer to the cost associated to an installation with and without reused batteries.

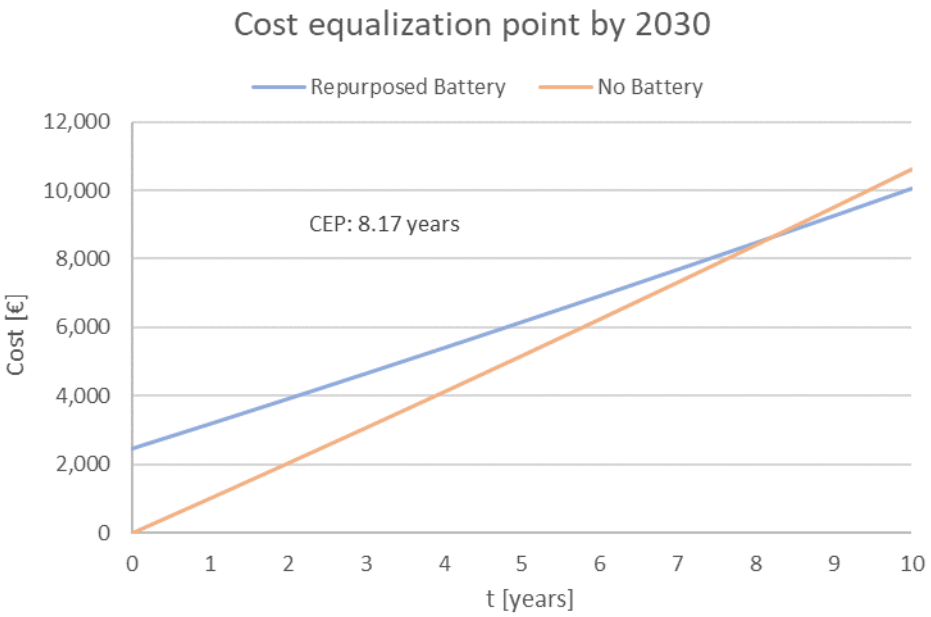

Figure 19. Expected CEP by 2030 if this strategy is used in conjunction with the Tesla Model 3 battery recharged using the grid energy. Own elaboration.

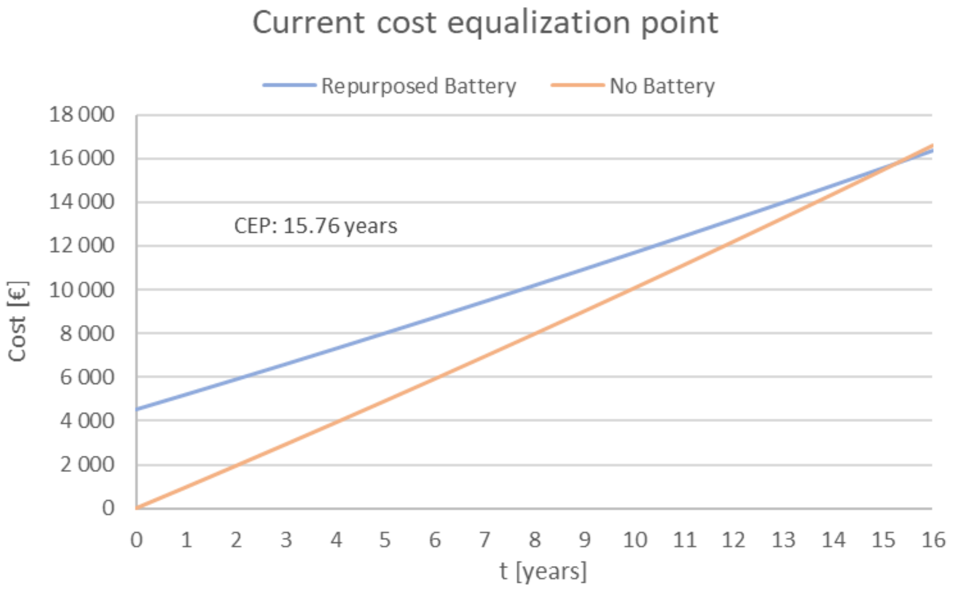

Figure 20. CEP that would be achieved today if this strategy is used in conjunction with the Tesla Model 3 battery recharged using the grid energy. Own elaboration.

Considering the lifetime obtained by the battery model, the above application would not be profitable in either situation since the cost equalization point is beyond the expected lifetime of the battery. Considering a 75% SoC value at the start of its second life, the 55kWh Tesla Model 3 battery would be able to run uninterrupted for 7.65 years today and 6.91 years in 2030.

As presented, the energy consumption strategy is not viable for either of the two situations presented above, since the cost equalization point is reached, once the battery is no longer useful in its second life. However, a significant improvement is observed in 2030, mainly due to the lower cost per kWh.

At present, the inverter and battery are too high an investment to be able to compete with the price of contracted electricity. Whereas it is expected that the price of the inverter, as well as the battery, will be reduced, as there are currently no proposals specifically adapted to the proposed activity. As soon as the costs of reused batteries and inverters are lower than they are at present, there may be interest on the part of users to equip their homes with used batteries. This downward trend in the cost of obtaining these devices can be seen in the reduction of the expected recovery point by 2030.

7.2.2. Repurposed battery to increase photovoltaic self-consumption

This second proposed energy optimisation strategy requires the use of more elements for its operation, as the initial investment price will be higher than in the previous strategy. In addition to the inverter and the second life battery, this installation requires a PV system consisting of the necessary PV panels plus a battery charge regulator.

The following Table 12 shows the current price of the above elements and their expected price in 2030.

	Price today [€]	*Price in 2030 [€]*	*Efficiency [%]*
Tesla Model 3 repurposed battery	2716	1253	90
Inverter	≈1600	≈1200	99
Photovoltaic panel	≈220	≈150	20

Table 12. Initial investment for photovoltaic self-consumption increase strategy to optimise energy consumption [36].

In the same way as in the previous situation, the following Figures 21 and 22 show the evolution of the expenses, that would be obtained using this second strategy or in the traditional way using only grid energy. And in the same way as before, the values represented in the following graphs have been calculated using equations 8 and 9 of chapter 6.2.

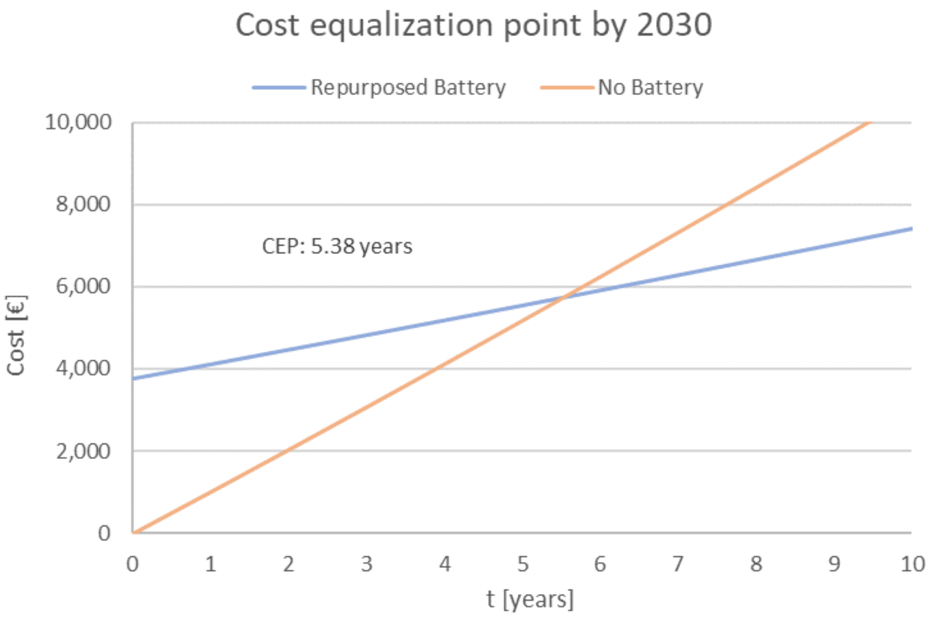

Figure 21. Expected CEP by 2030 if this strategy is used in conjunction with the Tesla Model 3 battery to optimise energy consumption. Own elaboration.

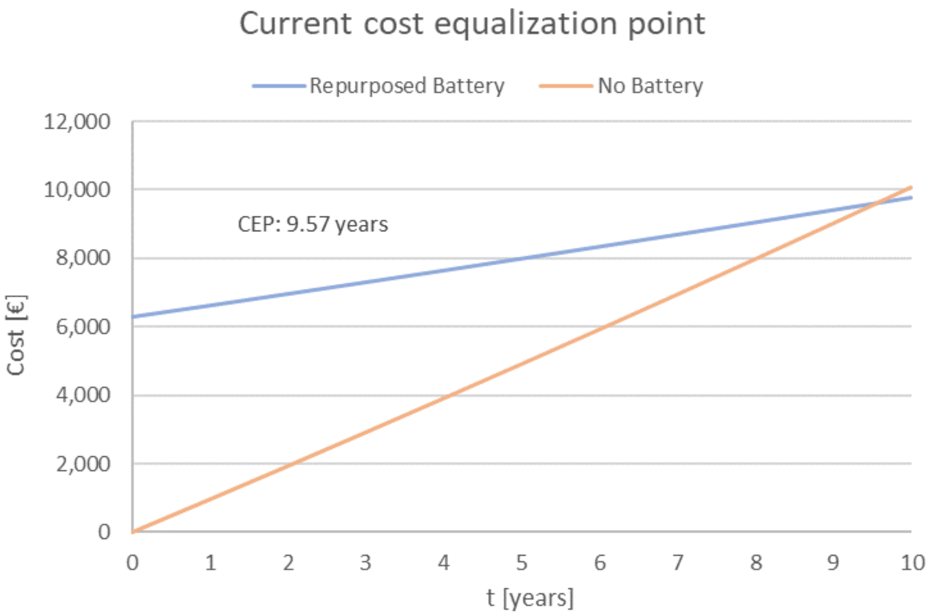

Figure 22. CEP that would be achieved today if this strategy is used in conjunction with the Tesla Model 3 battery to optimise energy consumption. Own elaboration.

This second application presents encouraging results. On the one hand, by 2030, from 5.38 years onwards, the cost associated with this second strategy would be lower than the cost associated with non-battery energy consumption. On the other hand, this application would not be profitable at present, because for this to happen, the costs associated with energy consumption with this second strategy would have to be lower than the costs of energy consumption from the grid and this happens after 9.57 years, but the useful life of the Tesla Model 3 battery is up to 7.65 years.

7.3. CO_2 emissions results

This third section of the results chapter presents the average CO_2 emissions associated with the different energy consumption strategies in EU households. As shown in section 4.3, the trend is downward, due to the different regulations that are being applied to address the worldwide issue of global warming. As the results obtained from official sources only represent the values of CO_2 generation per kWh produced up to 2016, a linear regression has been performed to estimate both current values and CO_2 emissions values for 2030. All values are included in Table 18 in the appendix.

The following Figure 23 presents the values of CO_2 emissions for the two strategies studied in this thesis comparing their results with the emissions originated by the normal energy consumption with the standard tariff of hourly discrimination. To obtain the results in this section, the grams of CO_2 generated per kWh were multiplied by the kWh of electrical energy used. In the case where a second-life battery is used, these kWh of energy used refer only to electrical energy during off-peak hours. While for the installation, which does not contemplate the use of the battery, the total kWh used daily are considered.

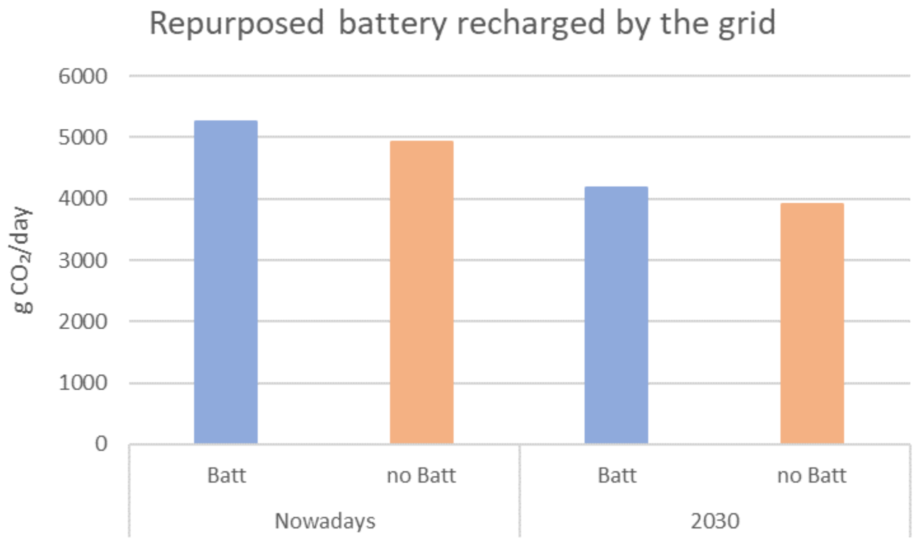

Figure 23. Expected CO_2 emissions per year for the first strategy using second-life batteries and for a standard tariff. Own elaboration.

As introduced at the beginning of this chapter, these emission values of grams of CO_2 have been obtained by multiplying the estimated values of grams of CO_2 for the year, shown in Table 18 in the appendix, from which the installation of second life batteries is to be implemented by the kWh of electricity used, both in peak and off-peak hours.

In the case of no battery use, as shown in Table 6, the daily electricity consumption of 17.52 kWh today and 18.72 kWh by 2030 is represented. If we multiply these values by the amount of grams of CO_2 referred to each year, we can obtain the values shown in the table above in reference to the situations without a second life battery.

For this configuration where the battery is charged by grid electricity, due to the efficiency of the process, more energy is required than in the case of not using that battery. This electricity value is equal to the sum of the consumption during off-peak hours plus the energy stored in the battery, both values also shown in table 6. In the same way as in the previous case, if we multiply the total value of daily electrical energy required by the value of grams emitted that year by the generation of 1 kWh, we obtain higher emission values than in the situation of not using a second-life battery.

These first results received for the strategy that implements second-life batteries, which are recharged with energy from the grid during off-peak hours, do not seem very encouraging. If we focus first on the number of grams of CO_2 emitted by this first strategy, we observe a positive trend with respect to its reduction, as previously introduced. The CO_2 emissions expected for 2030 represent a 20% reduction.

However, even though the CO_2 emission values are reduced compared to current values, the emissions associated with the second-life battery installation are higher, by the reason of higher energy requirement for the battery charging. This increase in energy use is due to the fact, that the charging and discharging process of the battery is not 100% efficient and therefore, this first strategy requires approximately 11% more energy for the complete charging and discharging cycle to be completed.

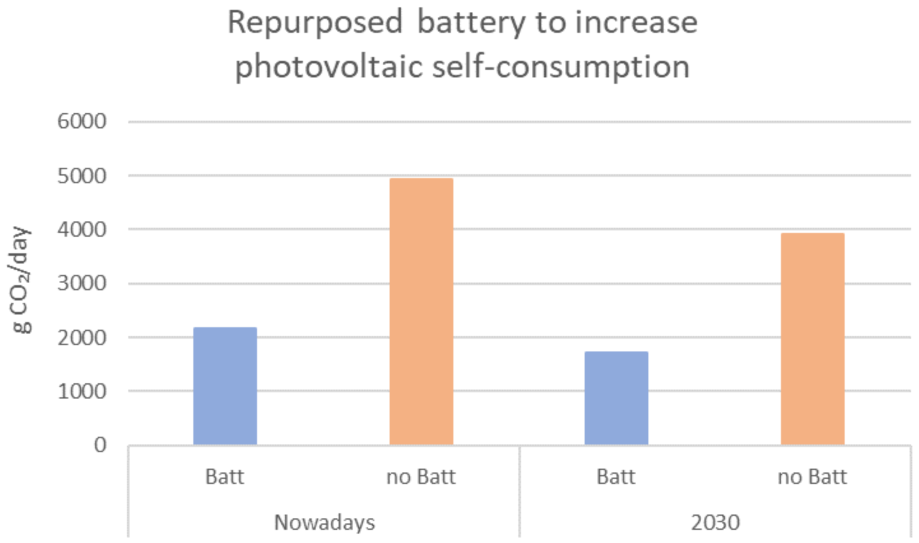

Figure 24. Expected CO_2 emissions per year for strategy to increase photovoltaic self-consumption and for a standard tariff. Own elaboration.

The values represented in Figure 24 above have been obtained in the same way. The emissions in the case of not using a battery are the same as in the previous situation, but the emissions associated with the installation with a second-life battery are already reduced here. This reduction is due to the recharging of the battery with clean energy from the sun. In this case, the electricity from the grid is only used during off-peak hours, thus reducing the link to energy that emits emissions due to its generation.

The results obtained for this second strategy are encouraging, although they are based on ideal conditions that are very difficult to meet in many parts of the European Union. The most important one of them, are the hours of sunlight during the day, since this installation aims to charge the batteries through solar panels and then use them during peak hours.

If we focus on the values shown, they present notable differences with respect to those introduced previously. In the latter case, since the use of energy provided by the grid is much lower, CO_2 emissions are reduced by as much as 56%.

As noted above, it is not possible for the conditions required by this second strategy to be met, to achieve the results presented. A detailed study should be carried out for each region, in order to determine in detail the percentage of utilization of this second strategy. A possible solution, which is not contemplated in this thesis, would be the use of both strategies combined to be able to make the most of the potential of both, and to adjust to the climatological conditions of each region and as well as each season of the year.

7.4. Other country-focused results

The above results show the remaining useful life of the Tesla Model 3 55 kWh battery, if deployed today and in early 2030 for energy storage applications in European households, considering the overall energy consumption.

As presented in section 4.1, there is a large variability in energy usage per capita within the EU. This average value considered in the previous calculations has a current value of 17.52 kWh. On the one hand, it can be observed, that countries such as Malta, Portugal and even Spain have energy consumption values per capita that are much lower than the value above. On the other hand, countries such as Finland, Austria and Germany exceed the average levels.

This section will focus on the same results as in the previous one that would be obtained for each of the two energy optimisation strategies if, instead of using the 17.52 kWh value, the energy utilization of countries above and below the average value were considered. The following Figure 25 represents this difference in energy usage taking as an example Spain, with a daily use per capita 57% lower than the European average value (9.97 kWh), and Austria, with a daily consumption per capita 37% higher than the European level (24.02 kWh).

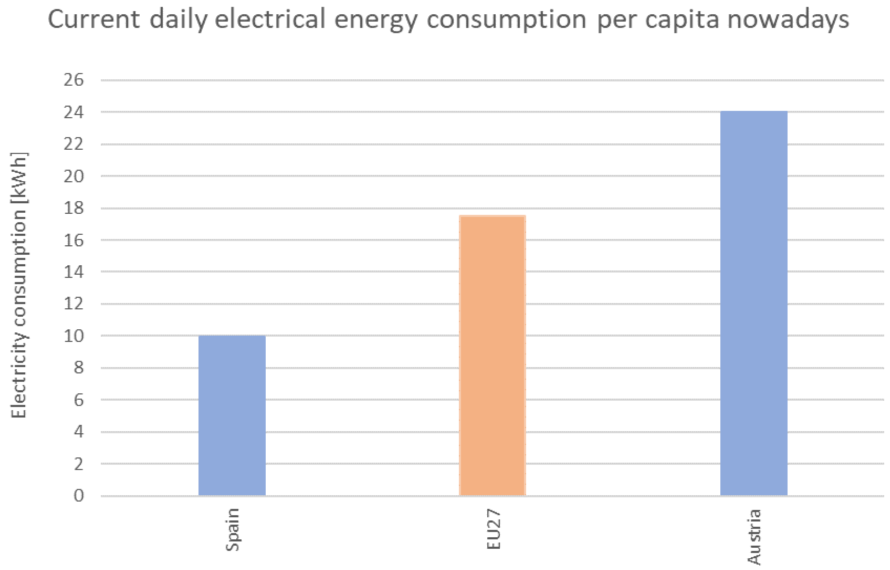

Figure 25. Difference in per capita daily energy consumption in the EU at present. Own elaboration.

This study focuses on the implementation of these energy optimisation applications, using second-life batteries to be deployed in the early 2030s. In this way, these energy consumptions should be reflected in expected energy utilization for that year. Therefore, the expected average European usage would be 18.72 kWh, the consumption in Spain would be 10.65 kWh and 25.66 kWh in Austria.

7.4.1. Second-life application powered by the Tesla Model 3 battery

Once the energy usage is known, in the same way as in the previous case, the portion of energy that would be consumed during peak hours in 2030 would be calculated. In other words, the amount of energy that the Tesla Model 3 battery would have to store, as well as the DoD and, finally, the remaining useful life.

The following Table 13 summarises the information presented above:

	EU Average	*Spain*	*Austria*
Energy consumption	18.72	10.65	25.66
DoD [%]	31.38	17.86	43.01
Lifespan	6.91	14.75	3.88

Table 13. Comparison of the remaining battery life of the 55 kWh Tesla Model 3 in different energy demand scenarios in 2030. Own elaboration.

From the values obtained, a close relationship can be drawn between battery life and energy consumption. The more energy the battery has to supply to the system to power the household during peak hours, the greater the depth of discharge and therefore the shorter the lifetime of the battery.

These results allow us to appreciate the behaviour of the studied battery under different states of daily energy demand in different EU countries. In this way, it is necessary to study each specific case, being able to observe, depending on its energy demand during peak hours, which battery would best suit it in order to extend its useful life and achieve the cost equalization point in the shortest time possible.

In the Austrian case, which requires the battery to store a total of 16.13 kWh in 2030 to supply the energy needed during peak hours, there is a depth of discharge of about 43% in each cycle. This high discharge at each use causes this premature deterioration of the battery, which would only be useful for a short period of time (3.88 years). For these strategies to be successful in this region, it would be necessary to use a battery with a second-life capacity greater than the 37.5 kWh capacity of the Tesla Model 3 battery.

Spain is in a different situation. The average consumption during peak hours is much lower than in the previous case and the battery should store a total of 6.7 kWh. Therefore, the depth of discharge is reduced to about 18% and thus the Model 3 battery shows encouraging results providing an uninterrupted use of about 15 years. In this case, there is more flexibility to install another battery with a lower capacity and accordingly reduce the initial investment.

The following Figure 26 reflect the information presented above regarding the remaining useful life for each country:

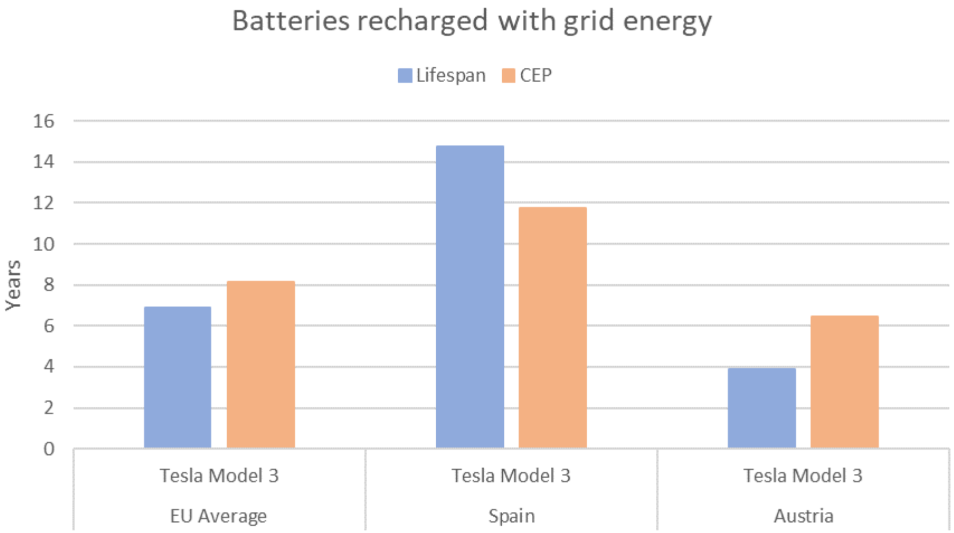

Figure 26. Remaining Tesla Model 3 battery life and CEP for the Spanish and Austrian cases, considering the first energy optimization strategy. The EU case is presented as a reference. Own elaboration.

For this first case, which considers the installation of the energy optimization system with the second life battery charging system using grid energy, there is a notable difference in relation to the country where this system is to be implemented by 2030.

Due to the large difference in power consumption, and therefore the amount of power the battery must provide during peak hours, this huge difference in remaining life of almost 11 years is observed. In the case of Austria, the average daily energy consumption per capita is expected to be around 25.66 kWh by 2030, 14.37 kWh of which will be consumed during peak hours. If these kWh of peak energy are to be provided by making use of the second-life battery system, taking into account that it is not 100% efficient, the battery will have to discharge 16.13 kWh of its maximum capacity of 37.5 kWh. Referring the example of Spain, this energy requirement during peak hours is expected to be 5.97 kWh by 2030. Therefore, the Model 3 battery with an initial capacity of 37.5 kWh will have to provide a much lower amount of energy than the Austrian case, thus concluding with this large difference with respect to its lifetime.

However, according to the cost equalization point, we observe a change in behaviour. The CEP is determined by matching the costs associated with the two energy consumption tariffs, in this case the strategy with the second-life battery and the standard energy consumption tariff. In Austria, the cost equalization point is reached earlier, but this is not sufficient to consider this strategy viable for Austria. But for the Spanish case, due to the high expected useful life, there is a wide range of time to consider this strategy viable.

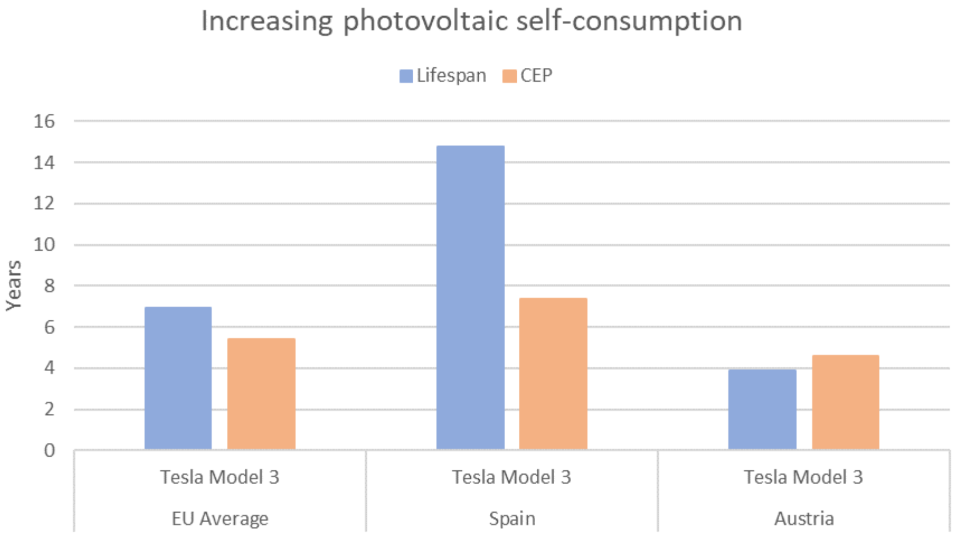

Figure 27. Remaining Tesla Model 3 battery life and CEP for the Spanish and Austrian cases, considering the second energy optimization strategy. The EU case is presented as a reference. Own elaboration.

The results observed after studying this second strategy are even better than the previous one, since it leads to an improvement in each case. As far as the useful life in both cases is concerned, it maintains the values presented above, as the batteries provide the same amount of energy. But the CEP has been reduced in both cases.

Even this cost equalization point reduction, considering that the ideal conditions required are met, is still not feasible for the Austrian case, since the energy required in this country consists of a large portion of the energy stored in the battery. In this case, it is necessary to use a battery that presents a higher initial capacity than the Tesla Model 3, and this is what is presented in the section below.

7.4.2. Matching the depth of discharge (DoD)

As introduced above, in the case of Austria it is necessary to implement a battery with a higher capacity than the 37.5 kWh of the Model 3. Therefore, this second scenario consists of implementing a battery in each case, whose depth of discharge is the same as the one, that occurs for the average daily per capita consumption value in the European Union with the Model 3 battery. Which means, that for the cases of implementation of these installations with second life batteries in Spain and Austria, the depth of discharge of these batteries should be close to 31%. This is achieved by reducing the depth of discharge of the Austrian battery and increasing the depth of discharge for the Spanish battery. The following Table 14 presents the 2 new batteries considered and the exact DoD for each of them.

	EU Average	*Spain*	*Austria*
Battery	Tesla model 3	Mini Cooper SE	Audi e-tron 50
Second-life capacity [kWh]	37.5	21.68	48.53
DoD [%]	31.38	30.89	33.24
Lifespan	6.91	12.25	5.50

Table 14. Remaining lifetime values for batteries in the different scenarios with similar DoD. Own elaboration.

What is achieved by incorporating these batteries to match the depth of discharge, is a reduction of the lifetime in the case of Spain, and an increase of the battery lifetime in the example of Austria. As in the previous section, the lifetime and the cost equalization point for each scenario are plotted and compared with the results previously obtained with the Model 3 battery.

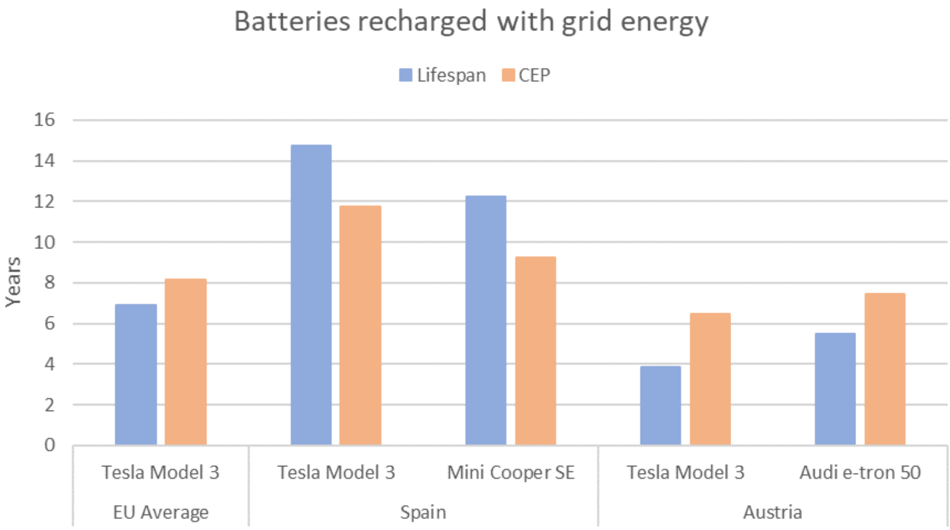

Figure 28. Remaining battery life and CEP for the Spanish and Austrian cases, considering the first energy optimization strategy for the same DoD. Own elaboration.

Referring to the example of Spain, the implementation of the Mini Cooper SE's 21.68 kWh second-life battery continues to show encouraging results, even with the reduction in capacity, the useful life of the battery continues to exceed the CEP.

On the other hand, this is not the case in Austria. The strategy of energy optimization by charging the battery via the grid is still not viable, even when using a higher capacity battery such as that of the 48.53 kWh Audi e-tron 50. Even so, improvements are observed in reducing the difference between CEP and battery lifetime.

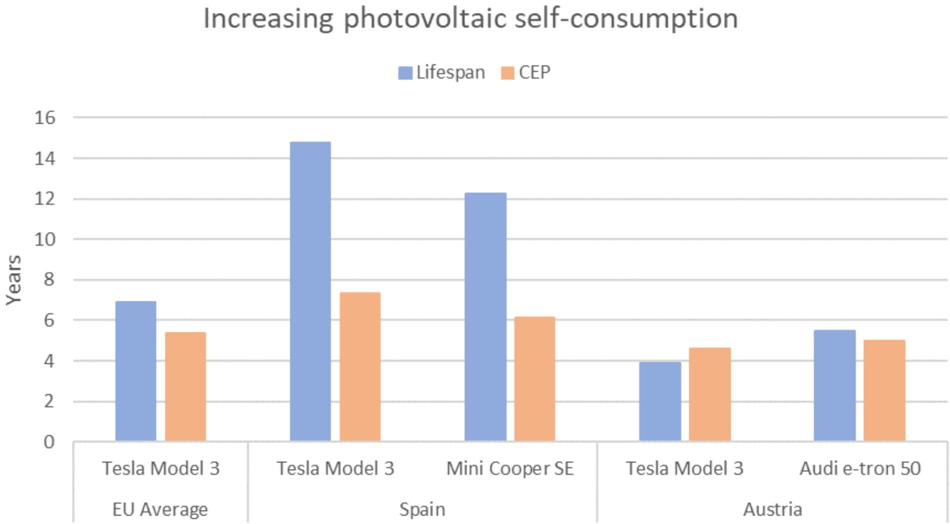

Figure 29. Remaining battery life and CEP for the Spanish and Austrian cases, considering the second energy optimization strategy for the same DoD. Own elaboration.

This last Figure 29 presents the best results observed so far, as it shows, that this second energy optimization strategy is feasible for both cases. The big difference is that in the Austrian example, the CEP is reduced to below the battery life of the Audi e-tron 50. As already indicated several times before, these results are obtained considering that the ideal conditions implemented for this second strategy are fulfilled.

8. Conclusions

The objective of this thesis was to analyze the economic feasibility of introducing a system composed of second-life lithium-ion batteries to achieve energy optimization in stationary storage applications, especially focused on private residences. To achieve this study, two energy optimization strategies, employing the use of second-life batteries, were presented and analyzed in different scenarios to test their viability.

The use of second-life batteries will become a reality by the beginning of the next decade as soon as the number of outdated electric vehicles becomes a serious problem. This new niche market will offer multiple advantages to users, who opt for these applications because even if the batteries of electric vehicles are considered inoperable after their first life, there is still a great potential that can bring great benefits.

The advantages presented so far, in relation to second-life batteries are not limited only to the use of cheaper technology and avoidance of the resources and emissions associated with the manufacture of new batteries. The material benefits to the end user are tangible, such as a 42% price reduction compared to new batteries. The reuse of batteries will also bring additional benefits to the parties involved. Automotive manufacturers will be able to save an average of $67 per reused battery unit instead of recycling them. The industry and supply chain created around reuse will generate additional jobs and revenue (about $79 million in 2030 for the 93,000 viable battery packs for electric vehicles) [20].

The importance of this project relies on the benefits that these batteries can provide and present some ways to use these second-life batteries to improve aspects of daily life. The results obtained through the model presented seem quite encouraging but there is still a lot of work to be done in this sector to analyze in more detail the best way to get the best out of these batteries.

This thesis has so far focused on estimating the remaining lifetime and feasibility of a group of batteries with a wide range of capacities in order to observe their possible implementation for lower energy demand applications by 2030. Concerning the useful life obtained by the calculation procedure defined in the article based on lithium batteries [28], it strictly depends on the state of charge of the battery, normally between 70% and 80% [2,3]. In this first step, results ranging from approximately 2 years (for the Fiat 500e battery with a 75% SoC) to approximately 9 years (for the BMW iX3 battery with a 75% SoC) have been obtained. These results fit quite well with the currently estimated values for the possible longevity of these batteries, which is expected to be between 5 and 8 years [29].

Simultaneously, two strategies have been defined that combine the use of second-life batteries with the grid, as defined in section 5. Although both are very similar in that they use batteries from EVs, they differ greatly in the aspect of how the battery is charged, one offering a more sustainable way of charging than the other. The use of one or the other strategy will be defined by the atmospheric conditions of the geographical region where it is to be implemented, as one requires the use of solar panels to charge the battery during sunlight hours. The use of this more sustainable strategy will, by 2030, reduce CO_2 emissions from the generation of kWh of electricity by more than 50% compared to using energy from the grid to charge the battery.

The viability of these installations will be largely defined by the high initial investment cost of the entire installation (battery, inverters, PV panels, etc.). The cost per kWh of battery capacity is expected to drop from the current \$75 to \$100 [30,31] to \$40 by 2030 [20]. The price of inverters is also expected to fall as they will be adapted exclusively for this type of application in the coming years.

The cost equalization point (CEP) is defined to observe how many years would be necessary to equalise the accumulated cost of installations with a second-life battery with the accumulated cost of electricity consumption from the grid through a two-period energy tariff. If the longevity of the battery exceeds the CEP, it is considered that this battery could be viable for use in this installation in the future. This CEP has different values depending on the capacity of the battery and the energy it has to provide. For example, in the case of using the Tesla Model 3 battery for an average European consumption, there is a difference of almost 3 years to settle this CEP. This means that depending on the battery charging strategy used, an installation may or may not be viable after 2030.

The study of more specific cases, such as Spain and Austria, can provide values that are closer to reality than considering only average values for the EU. The average Spanish electricity consumption is lower than the average European value, so that even using a battery smaller than that of the Tesla Model 3, it would be possible to achieve a situation where the installation is viable. Because it is a country with a very high rate of sunlight hours during the year, it would be possible to opt for a charging strategy with photovoltaic panels, thus reducing the CEP and providing a more sustainable charging configuration. In the case of Austria, on the contrary, having an average electricity consumption value higher than the EU average value and having a lower sunlight hours index than Spain, the possibility of using a mixed charging configuration should be studied in order to maximise the viability of the installation.

The future of the electric car is very exciting, due to its rapid evolution. Batteries will play a fundamental role in the consolidation of the electric vehicle over the classic internal combustion vehicle or hybrid vehicles and as engineers we must contribute to impart a life cycle of the batteries as sustainable as possible and get the most out of them.

9. Appendix

Table 15: Global electric passenger car stock, 2010 - 2020.

Year	*China*		*Europe*		*United States*		*Others*[11]		*World*	
	BEV	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*
2010	0.0016	0.0003	0.0071	0.0001	0.0038	0.0000	0.0045	0.0000	0.0169	0.0004
2011	0.0063	0.0007	0.0173	0.0005	0.0135	0.0080	0.0181	0.0003	0.0552	0.0095
2012	0.0160	0.0009	0.0357	0.0098	0.0282	0.0466	0.0345	0.0128	0.1143	0.0701
2013	0.0306	0.0017	0.0670	0.0361	0.0759	0.0956	0.0519	0.0285	0.2253	0.1618
2014	0.0594	0.0259	0.1255	0.0711	0.1393	0.1509	0.0829	0.0481	0.4071	0.2960
2015	0.2061	0.0866	0.2102	0.1696	0.2103	0.1938	0.1016	0.0668	0.7282	0.5167
2016	0.4631	0.1656	0.3012	0.2889	0.2971	0.2667	0.1234	0.0866	1.1847	0.8077
2017	0.9311	0.2766	0.4309	0.4297	0.4016	0.3605	0.1667	0.1407	1.9303	1.2075
2018	1.7470	0.5418	0.6318	0.6069	0.6404	0.4830	0.2389	0.2040	3.2580	1.8358
2019	2.5812	0.7679	0.9683	0.7695	0.8823	0.5677	0.3292	0.2567	4.7610	2.3619
2020	3.5125	0.9962	1.7594	1.4004	1.1387	0.6394	0.4391	0.3101	6.8496	3.3461

Table 15. Global EV Outlook 2021. Trends and developments in electric vehicle markets. Global electric passenger car stock, 2010 - 2020 [18].

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[11] Others includes: Australia, Brazil, Canada, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

Table 16: Global electric passenger car sales, 2010 - 2020.

Year	*China*		*Europe*		*United States*		*Others*[11]		*World*	
	BEV	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*	*BEV*	*PHEV*
2010	-	-	-	-	-	-	-	-	-	-
2011	0.0048	0.0003	0.0102	0.0004	0.0098	0.0080	0.0136	0.0003	0.0383	0.0091
2012	0.0096	0.0003	0.0185	0.0093	0.0147	0.0386	0.0164	0.0125	0.0591	0.0606
2013	0.0146	0.0007	0.0313	0.0263	0.0477	0.0490	0.0175	0.0157	0.1110	0.0917
2014	0.0288	0.0243	0.0585	0.0350	0.0634	0.0554	0.0310	0.0197	0.1818	0.1343
2015	0.1467	0.0607	0.0847	0.0985	0.0711	0.0428	0.0187	0.0187	0.3211	0.2207
2016	0.2570	0.0790	0.0910	0.1194	0.0867	0.0729	0.0218	0.0197	0.4565	0.2910
2017	0.4680	0.1110	0.1297	0.1408	0.1045	0.0939	0.0433	0.0542	0.7455	0.3998
2018	0.8159	0.2652	0.2009	0.1772	0.2388	0.1225	0.0722	0.0633	1.3277	0.6283
2019	0.8342	0.2261	0.3366	0.1626	0.2419	0.0847	0.0903	0.0527	1.5030	0.5261
2020	0.9313	0.2283	0.7911	0.6309	0.2564	0.0717	0.1099	0.0534	2.0886	0.9843

Table 16. Global EV Outlook 2021. Trends and developments in electric vehicle markets. Global electric passenger car sales, 2010 - 2020 [18].

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[11] Others includes: Australia, Brazil, Canada, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

Table 17: Current and expected second-life battery purchase price for 2030.

Manufacturer	*Model*	*Initial capacity 100% SoC [kWh]*	*Remaining capacity 75% SoC [kWh]*	*Current acquisition cost [€]*	*Acquisition cost in 2030 [€]*
Fiat	500e	23.8	17.85	1,293	596
BMW	i3	27.2	20.40	1,477	682
Mini	Cooper SE	28.9	21.68	1,570	724
Nissan	Leaf	36	27	1,955	902
Hyundai	IONIQ	38.3	28.73	2,080	960
VW	ID.3	45	33.75	2,444	1,128
Tesla	Model 3	50	37.50	2,716	1,253
Renault	ZOE	52	39	2,825	1,303
Audi	e-tron 50	64.7	48.53	3,514	1,621
BMW	iX3	74	55.50	4,020	1,854

Table 17. Current and expected second-life battery purchase price for 2030. The current acquisition cost has been calculated considering an average value of the price per kWh between 75 and 100 $, while the cost by 2030 has considered the value of 40$ per kWh. Own elaboration.

Table 18: Evolution of emissions intensity of grams of CO_2 per kWh of electrical energy produced in EU from 1990 to 2030.

Year	*g CO_2/kWh*	*Year*	*g CO_2/kWh*	*Year*	*g CO_2/kWh*
1990	523,6	2004	399,1	2018	295,6
1991	511,2	2005	395,3	2019	288,4
1992	486,6	2006	396,2	2020	281,1
1993	468,2	2007	400,9	2021	273,9
1994	468,2	2008	376	2022	266,7
1995	454,6	2009	360,7	2023	259,4
1996	442,7	2010	346,9	2024	252,2
1997	431,5	2011	352,7	2025	245,0
1998	434,1	2012	353,2	2026	237,7
1999	417,4	2013	333,7	2027	230,5
2000	404,8	2014	320,4	2028	223,3
2001	402,8	2015	314,4	2029	216,0
2002	407,8	2016	295,8	2030	208,8
2003	410,6	2017	302,8		

Table 18. Evolution of emissions intensity of grams of CO_2 per kWh of electrical energy produced in EU from 1990 to 2030. The values up to the year 2016 have been extracted from an official source [24] while the remaining values have been obtained by a regression.

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