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Study of a battery collection and repurposing for a second life plant

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Abstract

The purpose of this study is to analyse the technical and economic feasibility of establishing a recovery and recycling plant that will receive used lithium ion batteries from electric vehicles (EVs).

This battery type is currently the most used in the automotive sector and they are the most expensive component of the vehicle as they comprise several valuable materials. Thus, reducing this cost by extending the application life of the battery or by recycling its materials appears to be an attractive solution to boost their market penetration.

Three different strategies for discarded EV batteries will be assessed: direct reuse, repurpose or recycling. Furthermore, several potential applications for second life batteries will be analysed from an economic, environmental and social point of view.

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1. Aim

The aim of this study is to evaluate the economic and technical feasibility of a collection and repurposing for a second life plant, which will receive lithium-ion batteries used in electric vehicles.

Different options for the end of life of the battery will be analysed, including second life applications and recycling.

2. Scope

In this study all the stages from the retrieval of the battery until it is finally refurbished or recycled are to be considered.

First, it will be necessary to analyse the reverse logistics for their retrieval. Proper handling throughout storage and transportation are required to minimize possible damages. An optimization study will be carried out for the accurate and efficient retrieval of batteries.

Secondly, the economic feasibility of creating a battery collection and repurposing for a second life business model will be assessed.

Several factors will be taken into account for choosing the location of the plant and the recycling technology to be used.

Once in the plant, batteries can be recycled or go through a reconfiguration process to be reused in a new application. This will involve a disassembly process after which modules or cells are grouped within different capacity ranges and are ready for reinstallation.

An economical study to determine the cost of recycling and reusing and therefore the viability of this new model is included as well.

Finally, various applications for second life batteries are proposed considering the sustainable business model concept. That is, analysing not only the economic variables but also taking into account the environmental and social impact of each solution.

3. Requirements

The following conditions will be taken into account for the project development:

- The project will be developed considering the current market characteristics regarding the energy price and the future market characteristics concerning the batteries availability.
- The economic feasibility will be computed from the moment the battery is acquired after its first useful life and not from its manufacturing.
- Only two specific models of EV batteries will be considered in this study.
- The final decision regarding whether the plant should be created or not, will be made according to its financial viability.

4. Justification of the study

Lithium-ion batteries have recently experienced a rapid growth in the market: from having been used mainly in consumer electronics during the nineties and early 2000, they are now highly used in the automotive industry.

According to the International Energy Agency (Energy Agency, 2019), in 2018 the number of electric vehicles in the roads exceed 5,1 million units, up 2 million from the previous year and almost doubling the number of new electric car sales.

Figure 1 shows the overall trend is a continuous growing in the number of sales of electric and plug-in hybrids vehicles.

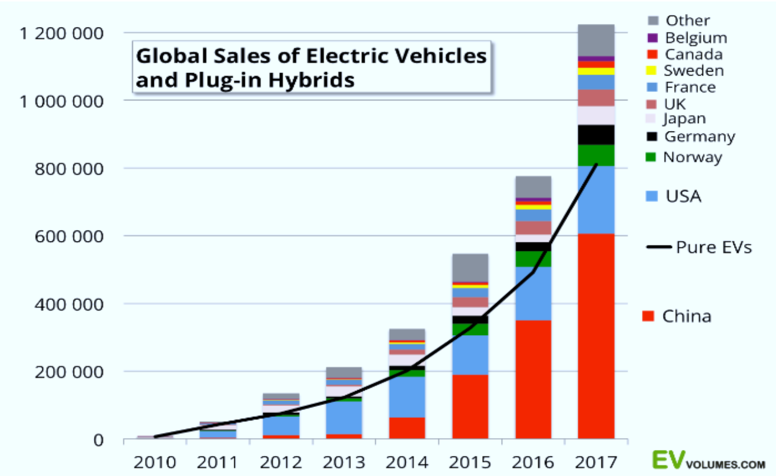

Figure 1. Global Sales of Electric Vehicles and Plug-in Hybrids. Source: EV-Volumes

Road transport is responsible for around 40% of NOx emissions in the EU, most of which comes from diesel-powered vehicles (Niestadt & Bjørnåvold, 2019). The pollution from road transport is especially harmful, as emissions released by vehicles occur close to the ground, often in areas where many people live and work.

As an effort to reduce environmental impact, governments impulse measures to promote energy efficiency and incentives for zero- and low- emissions vehicles in order to help bridge the cost gap between electric and conventional vehicles.

It seems clear that the amount of used batteries will increase drastically and nowadays there is a lack of regulatory policy on their disposal and fewer recycling facilities. Consequently, a huge number of discarded batteries end up in landfills without any recycling at all, contributing substantially to environmental pollution.

Some studies (Gaines, 2012; Zackrisson, Avellán, & Orlenius, 2010; Ziefle, Beul-Leusmann, Kasugai, & Schwalm, 2014) indicate that emissions of CO_2 and SO_2 and other pollutants from battery materials production represent a high fraction of an EV lifetime emissions. Moreover, materials such as lithium, are scarce and mined only in a few countries, so its future supply and availability may be threatened (Marcelo Azevedo, Nicolò Campagnol, Toralf Hagenbruch, Ken Hoffman, Ajay Lala, 2018). Moreover its extraction process is highly energy consuming (Pistoia & Liaw, 2018). The evolution of lithium demand in the recent years is illustrated in Figure 2.

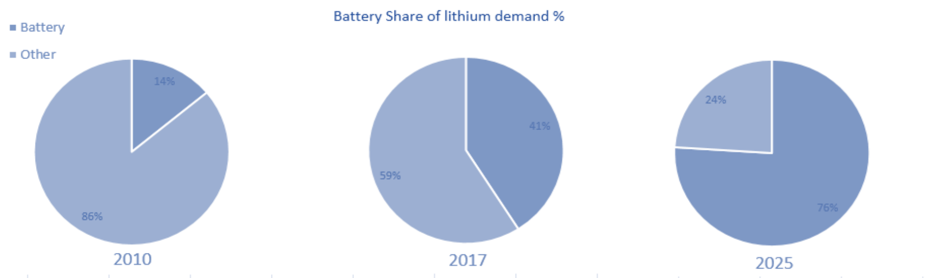

Figure 2. Evolution of lithium demand. Source: McKinsey Basic Materials Institute

Cobalt reserves are also of great concern, as several political and social problems arise from its extraction activity, which takes place mainly in Democratic Republic of the Congo (Harper et al., 2019).

Moreover, car batteries are not appropriate anymore when they have lost between 20 and 30% of their initial capacity (Wood, Alexander, & Bradley, 2011). However, they are still suitable for other less-demanding tasks, which can extend the batteries' operational lifetime into a second one.

Before its reuse, these batteries should follow an evaluation and transformation process. They have to be collected, checked and adapted, if necessary, to their new application requirements.

Cells or modules from the batteries that do not meet some minimum criteria and are not suitable for reusing, can be sent to recycle, and recover its materials (Charles Robert Standridge & Hasan, 2015; Warner & Warner, 2015).

Nowadays, there are recycling plants in several European countries, in the US, Canada and some Asian countries. The processes they use, and their efficiencies vary: from methods where the main benefit comes from recovering copper or cobalt (Melin, 2018; Charles R Standridge, Ph, Corneal, & Ph, 2014), to highly efficient ones that recover a considerable percentage of the material.

In Figure 3 we can see the location of some of the main recycling companies in Europe.

Figure 3. Location of recycling companies in Europe. Source: own elaboration

Many important vehicle manufacturers have seen potential on this field and have accomplished several initiatives to analyse different energy storage and stationary battery applications. In Table 1 some notable projects carried out lately can be checked.

Joint Ventures	**Description**	**Location**
Daimler GETEC/ the mobility house remondis/EnBW	Battery storage unit with a total capacity of 13 MWh using degraded EV batteries from Daimler EV models	Luenen, Germany
BMW/PG&E	18 months pilot project to demonstrate EV smart charging and optimization grid efficiency with participation of 100 BMW i3 owners.	San Francisco, USA
Nissan Sumitoto (4R Energy)/ Green charge network	System (600 kWh/400 kWh): 16 Nissan Leaf LIBs regulate energy from a solar plant	Osaka, Japan
BMW/Vattenfal/Bosch	2600 battery modules from 100 electric cars and provides 2MW of output and 2.8 MWh of capacity.	Hamburg, Germany
Renault/ Connected Energy Ltd	“E-STOR”: on-grid providing energy storage that prevents power grid overload and balances supply and demand.	United Kingdom, Europe
Mitsubishi/ PSA EDF/ Forsee Power/ MMC	Bi-directional battery energy consumption optimization from retired batteries	Paris, France
General Motors/ ABB	5 Chevrolet Volt LIBs, 74 kW solar array & two 2kW wind turbines to power a General Motors office building site	USA

Table 1. Second-life battery projects. Source: (Hossain et al., 2019)

All these aforementioned concerns culminate into the necessity of developing solutions for dealing with batteries when they reach their end of life as well as proactive regulations regarding collection and disposal and innovations in recycling technologies. Given that, this project provides an overview of the status of battery recycling and reusing and proposes the creation of a recycling and repurposing plant, providing a complete solution for extending batteries lifetime after they are removed from electric vehicles and for its appropriate recycling.

5. State of art

The entrance of electrical and plug-in hybrid electric vehicles into the transportation sector is seen as an environmental opportunity to advance towards a cleaner and more sustainable world (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013).

The biggest obstacle to rapid market penetration of these vehicles at the moment is the higher initial investment required when compared to conventional combustion engine ones (Coffman, Bernstein, & Wee, 2015) and the battery is the main component responsible for this high price. Therefore, developing strategies that will help reduce this cost seems to be the key to drive up its commercial viability (Ramoni & Zhang, 2013).

Electric cars have mostly lithium batteries for the power supply. These devices comprise valuable materials which can be recovered and reused (Weil & Ziemann, 2014) and this way help decreasing the price.

As batteries still retain 80% of its capacity when they are not useful anymore for electric vehicles (Ramoni & Zhang, 2013) it came out the idea of giving them a second life before recycling.

Currently, the supply of lithium-ion batteries that are coming into the market is still very small As most of the vehicle applications that are using these devices have been recently introduced into the market, they are still in the early phase of their life. That means that it will take five years or more before these batteries reach their end of life and are ready to be reconfigured for a new application or recycling (Warner & Warner, 2015).

Until then, further research must be undertaken in this field to develop an efficient closed loop system for the life of batteries.

Many efforts in the development of life cycle assessment to asses EV battery impacts are being done nowadays. However, unified guidelines or harmonized approaches for performing these analyses are non-existent and consequently they produce conflicting results when second use applications are considered, due to variability in assumption, scope of the applications and scenarios (Vanesa Ruiz, Brett, Steen, & Van Den Berghe, 2016).

Some important tasks for the future are to set a clear definition of the end of life to ensure a common understanding with considerations for life cycle assessment and tools for its evaluation (Vanesa Ruiz et al., 2016).

The type of tests necessary to asses battery reliability, safety and performance at the end of its first use need to be assessed and additionally, standards containing criteria guidelines for evaluating battery status and suitability for second use applications should be stablished. The only guide available for battery testing is the one developed by the United States Advanced Battery Consortium, which presents several inconveniences as the testing times are too long and is not feasible for any business to run them (Casals, 2014; United States Advanced Battery Consortium, 2015).

In the same way, if the automotive and battery manufacturers would include the possibility of on-board diagnostic capabilities to check the status of batteries and the capacity and this information was shared with the repurposing companies, the assessment of batteries could be streamlined (J. Neubauer, K. Smith, E. Wood, 2015).

The next barrier to deal with is the diversity between batteries and this would be solved by uniform sizes, shapes, geometries of battery cells and packs and arrangements of management devices that will promote ease of handling in manufacturing and use and can reduce costs (V. Ruiz & Di Persio, 2018).

Most car brands have a partnership or specific agreement with battery manufacturers. Moreover, each manufacturer is specialized in certain types of cells, designing them to fulfil the requirements provided for each car manufacturer. Consequently, there is a wide range of possibilities concerning the different aspects of batteries and this means that is very difficult to mix and match battery modules into second use applications (Warner & Warner, 2015).

The main differences between battery models are cell chemistry, functional characteristics of the battery, cell type, module dimension, power and capacity, refrigeration system implemented and the battery management algorithms (Advanced Automotive Batteries, n.d., Canals Casals & Amante García, 2016)

Standardisation efforts in the area of second use have been initiated by some organizations such as SAE ("J2997 (WIP) Standards for Battery secondary use - SAE International," 2020). Nonetheless, as second life usage is still to become mainstream, currently there is no proper regulation.

Many questions regarding legal issues such as the guarantee of the battery after its reconfiguration for a second use, need to be answered and stablished by regulation (Warner & Warner, 2015).

There are only available standards for automotive lithium-ion batteries such as ISO 12405-2:2012 and 62660-2, which can be effective to construct the new standards, considering safety as one of the main concerns, as it must be ensured for proper operation and handling with batteries.

It should be also mentioned some waste reduction directives in the EU that set goals for recycling. Under them vehicle manufacturers are responsible for collecting and recycling electric vehicles. It required that by 2015, only 5% (by weight) of an electric vehicle could be sent to landfill. But the reality is that not all vehicles taken out of service are collected through regular channels that direct them to recycling or recovering processes and not all countries have reached the recycling goals set (Steward, Mayyas, & Mann, 2019).

In the same line, over the years, the EU has taken various actions to support electric mobility. Measures encouraging the use of renewable electricity and smart charging have been developed and also support to develop and standardise charging infrastructure has been given (EEA, 2016).

To address all these issues, cooperation between relevant actors and stakeholders along the battery value chain is necessary for establishing a viable solution for EV battery second use (Vanesa Ruiz et al., 2016).

Other actives areas of research nowadays are the improving of lithium-ion battery performance and reducing costs which could lead to the expansion of their applications and at the same time, enable new technologies which depend on energy storage (Nitta, Wu, Lee, & Yushin, 2015).

Efforts are concentrated on improving electron transport, the mechanical properties of conductive media or increasing chemical and thermal stability, developing coatings to reduce decomposition of active materials and modifications of electrolyte solutions (Nitta et al., 2015).

Among the three key components (cathode, anode and electrolyte) of LIB, cathode material is usually the most expensive one with highest weight in the battery, which justifies the intense research focus on it (B. Xu, Qian, Wang, & Meng, 2012).

Currently, $LiCoO2$ (LCO) is used in the majority of commercial Li-ion batteries in the cathode and some of its limitations are the high cost, low thermal stability and fast capacity fade at high current rates or during deep cycling (Nitta et al., 2015).

The industry is focused on developing nickel-rich and cobalt-free cathodes, which can have an important repercussion in the supply chain because they will impact in the demand of critical battery materials and costs (Battery & Summit, 2013; Steward et al., 2019).

Concerning the anode, nowadays most of them are made of graphite (Nitta et al., 2015; Steward et al., 2019).

Alloy anodes have been investigated for lithium ion batteries for many years because of the potential for much higher capacity density and specific capacity than the carbonaceous anodes (Blomgren, 2017).

Another technology under research are the silicon anodes, which offer high energy density and power rating potential at a potentially lower cost than current graphite anodes (Kelleher and Energy API, 2019).

When it comes to the separator, investigations are focused on improving the coating separators, using for instance ceramic materials, so that they do not impede ion flux, salt diffusion or fluid flow (Blomgren, 2017).

Also the electrolyte composition has a high relevance as they determine the current density, the time stability, the reliability of a battery and the formation of solid electrolyte interface (Q. Li, Chen, Fan, Kong, & Lu, 2016).

In Table 2 we can see a review of some recent studies regarding the future development of batteries which show that there is a good likelihood that they will continue to improve in cost, energy, safety and power capability (Blomgren, 2017).

Area of research	**Reference**
Cathode materials	(Miao, Hynan, Von Jouanne, & Yokochi, 2019; Nitta et al., 2015; Sun, Lee, Lee, Chen, & Myung, 2013)
Anode materials	(Blomgren, 2017; Dimov, Kugino, & Yoshio, 2003; Kelleher and Energy API, 2019; Miao et al., 2019; Nitta et al., 2015)
Electrolyte	(Blomgren, 2017; Q. Li et al., 2016)
Separator	(Y. Shinohara, Y. Tsujimoto, 2002)

Table 2. Future battery materials studies. Source: own elaboration

5.1 Current recycling processes

The basic lithium-ion battery design consists of a group of inter-connected electrochemical cells which are made up of a negative electrode and a positive electrode separated and connected by an electrolyte.

Material used at the cathode includes $LiCoO_2$, $LiNiO_2$, $LiMnO_2$ and $LiFePO_4$ and the anode is made of graphite. The electrolyte for the EV battery is made of $LiClO_4$, $LiBF_4$ or $LIPF_6$ dissolved in organic solvent such as ethylene carbonate-dimethyl carbonate (K. Xu & Von Cresce, 2011) (Broussely et al., 2001)(Hu et al., 2009)

A high recovery of materials such as cobalt, lithium, manganese, nickel, aluminium, copper, steel and plastics is essential to ensure the growth and sustainability of the electrical vehicle market (Sonoc, Jeswiet, & Soo, 2015).

Current industrial processes are focused on recovering cobalt, nickel and other valuables metals as they have the highest economic values (Sonoc et al., 2015). However, the price of lithium has been multiplied lately due to its increasing demand and scarcity (BBVA, 2018), and it is expected to keep on increasing next years. In Table 3, the current prices of lithium ion battery materials are presented.

Material	Price ($/t)	Reference
Cupper	6154	metalonline.net
Nickel	14145	
Aluminium	1763,5	
Zinc	2279	
Cobalt	34500	
Lithium	10250	lme.com

Table 3. Lithium ion battery main materials prices. Source: own elaboration

Recycling procedures can be divided in four main types: mechanical processes, pyrometallurgical, hydrometallurgical and direct recycling. In Table 4 various articles concerning these four recycling methods are listed.

Recycling technology	Studies
Hydrometallurgy	(Chagnes & Pospiech, 2013; X. Chen et al., 2015; Leite, Carvalho, de Lemos, Mageste, & Rodrigues, 2017; Tanong, Coudert, Mercier, & Blais, 2016)
Pyrometallurgy	(Guoxing et al., 2016; Heelan et al., 2016; Larcher & Tarascon, 2015)
Direct recycling	(Ellis & Mirza, 2014; Huang, Pan, Su, & An, 2018)
Mechanical processes	(Shi, Chen, & Chen, 2018)

Table 4. Recycling technologies studies. Source: own elaboration

Pyrometallurgy uses high temperature to smelt valuable metals. It is widely used in the industry because of its simplicity and high productivity (Guoxing et al., 2016). A flow diagram of the Batrec's pyrometallurgical recycling process is shown in Figure 4.

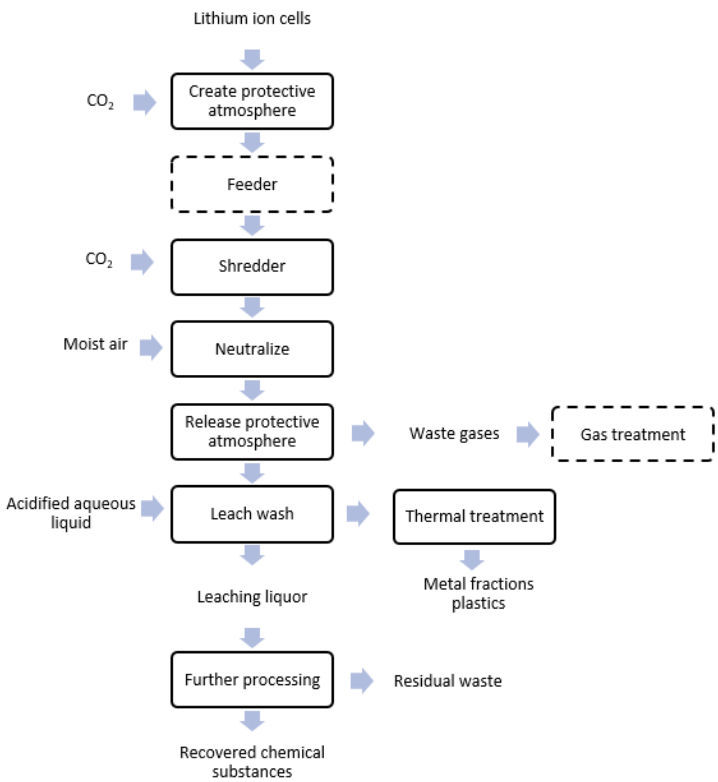

Figure 4. Batrec's pyrometallugical recycling process. Source:(Vadenbo, 2009)

Hydrometallurgy employs chemical processes to recycle. Due to the chemical complexity of the battery itself, several steps are followed: acid-base leaching, solvent extraction, precipitation and ion exchange and electrolysis. A diagram flow of the steps followed in the hydrometallurgical recycling process developed by Recupyl for lithium ion batteries can be checked in Figure 5.

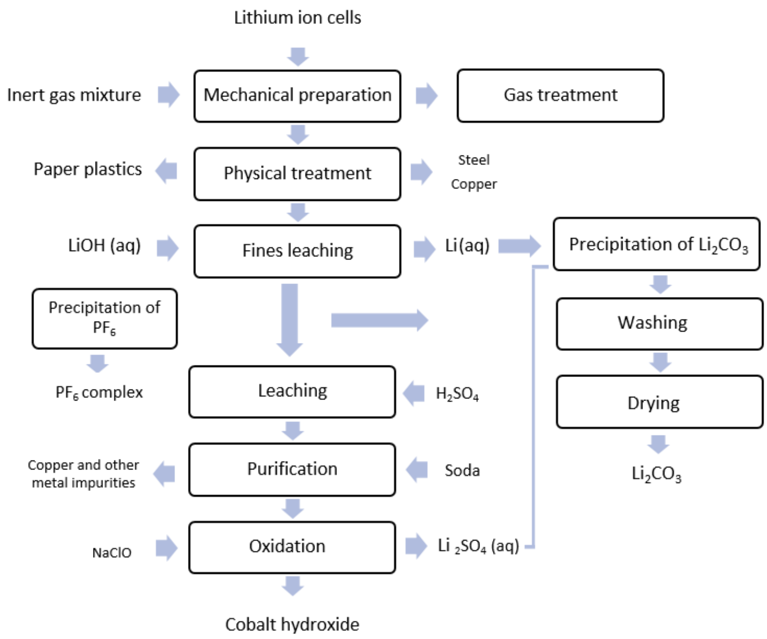

Figure 5. Recupyl's hydrometallurgical recycling process. Source: (Vadenbo, 2009)

In comparison with pyrometallurgical processes that are usually undertaken at high temperatures, hydrometallurgical methods have some advantages, as they are more environmentally friendly and they present higher recovery efficiency of valuable metals, especially Li, what makes it preferable for processing spent LIBs (Lv et al., 2018).

Direct recycling is a solvent extraction process where supercritical carbon dioxide (CO_2) is used to extract cathode and anode materials (Ellis & Mirza, 2014). A typical process consists in treating the cells with supercritical CO_2 which can extract the electrolyte. This way, the electrolyte can be recovered, and the cells are later dismantled and crushed. Then, the cell components are separated by physical techniques, subsequently the cathode materials are collected and can be reused (Huang et al., 2018).

There is also the possibility of recovering various materials by physical processes with minimal destruction. The materials obtained retain its crystal structure and have a good electrochemical performance (Shi et al., 2018).

After some of these processes, the material needs to go through some additional recovery steps (refining) to reach the level of purity required for reuse.

All these methods can be combined together to accommodate different incoming chemistry (M. Chen et al., 2019) and some existing recycling companies have developed their own in-house processes starting from them.

Table 5 provides an overview of the advantages and disadvantages of these four mentioned recycling technologies and a list of the recovered materials.

Recycling Method	Pros	Cons	Recovered Materials
Mechanical Processes	Applicable to any battery chemistry and configuration. Lower energy consumption.	Should be combined with other methods to recover most materials.	Li_2CO_3
Hydrometallurgy	Applicable to any battery chemistry and configuration. Low energy consumption. Recovery of lithium. High purity of material.	Only economical for batteries containing Co and Ni.	Copper, aluminium, cobalt, nickel, Li_2CO_3.
Pyrometallurgy	Applicable to any battery chemistry and configuration. Easy operation.	Only economical for batteries containing Co and Ni: gas clean-up required to avoid release. High energy consumption. Material loss. No recovery of lithium.	Cobalt, nickel, copper, some iron. Anode is destroyed.
Direct Recycling	Almost all battery materials can be recovered. Low energy consumption.	Recovered material may not perform as well as virgin material. Mixing cathode material could reduce value of recycled product.	Almost all components (except separators)

Table 5. Comparison of main recycling methods. Source: (Huang et al., 2018; Steward et al., 2019)

In Chapter 4, Figure 3 shows the location of the main recycling plants in Europe. Hereafter we are going to briefly explain the technology each of them uses.

5.1.1 UMICORE

By combining a unique pyro-metallurgical treatment and a state-of-the-art hydrometallurgical process, this Belgian company is able to recycle all types and all sizes of lithium-ion in a sustainable way ("Umicore," 2019).

The Umicore process is a smelting process for lithium-ion and nickel metal hydride batteries. First, an alloy of valuable materials (Co, Cu, Ni, Fe) is obtained from the smelter and then treated hydrometallurgical. All of the lithium, aluminium and manganese from the battery ends up in the slag which can be used in the construction industry or further processed to recover raw materials (Gaines, 2014).

The energy inside the battery components (electrolyte, plastics and metals) is used in order to reduce the consumption of energy and CO_2 emissions.

The process they have developed also differentiates itself by a higher metal recovery compared to existing processes and the output of products which can be directly reused in the market.

They avoid the use of any dangerous pre-treatment and they have implemented a gas cleaning system which ensures that no hazardous dioxins or volatile organic compounds are produced.

5.1.2 ACCUREC

This German company have developed their own process named Accurec's EcoBatRec which provides high safety and efficiency standards (ACCUREC, 2018).

It consists of an autothermal heat treatment followed by a comminution and a multistep mechanical treatment to recover aluminium, cobalt, NiCo, steel and stainless steel.

Previously to this, the cooling system of the battery is drained, and it is dismantled at cell or module level.

It requires low energy consumption and almost no off-gas emissions are produced. Moreover, they don't produce HF or hazard electrolytes emissions.

5.1.3 RECUPYL

Recupyl is a French company that recycles lithium-ion batteries and alkaline batteries. They are placed in France, Singapore and EEUU (RECUPYL, 2019).

In the Recupyl process batteries are shredded and then crushed. Both steps take place in an airtight enclosure filled with an inert atmosphere of argon and carbon dioxide, which prevents a violent lithium reaction. After the shredding, different fractions are obtained and then separated. The fines fraction rich in metal oxides and carbon is added to water so that lithium reacts with it and releases hydrogen gas. The water is heavily stirred, and the fines are added in a very controlled manner to prevent the accumulation of hydrogen gas and an explosion. Next, the water becomes rich in lithium hydroxide and lithium is recovered by adding sodium carbonate or phosphoric acid. The rest of the materials are recovered using a hydrometallurgical process.

5.1.4 SNAM

Snam is a French company whose main activity is recycling nickel-cadmium, nickel-metal-hydride and lithium-ion from batteries (SNAM, 2019).

They have traditionally worked with pyrometallurgy treatment units and they are also investing in the installation of hydrometallurgy treatment units to optimize its recycling performance.

On the other side, SNAM developed recently contractual agreements with international groups from the automotive industry such as Honda, Toyota, PSA Volkswagen or BMW. These agreements concern the collection in Europe and the recycling of their end-of-life EV and HEV batteries. Moreover, they collect batteries from many countries around Europe.

5.1.5 STENA

This Swedish company have a collaboration with Volvo, and they recycle around 38000 cars per year. They have reached rates of recycling of 95% of the car (Stena, 2019).

They handle all the steps of the waste car management: from packaging and collection, transport to processing in their treatment facilities and final delivering.

5.1.6 REDUX

They have recycling facilities in Germany and Austria, and they collect batteries from all around Europe ("Lithium-Ion Batteries - REDUX – Smart battery recycling," 2019).

They save energy by using the energy released when discharging batteries and feed it into the power grid.

They retrieve stainless steel, aluminium, copper, plastics and active materials from the cells, and they have achieved recycling efficiencies between 60 and 70%.

5.1.7 DUESENFELD

Duesenfeld, located in Wendeburg, Germany, combines mechanical and thermodynamic processes rather than using conventional battery melting or pyrolysis (“Duesenfeld | Recycling of lithium-ion batteries,” 2019). This recycling process requires less energy, recovers more raw materials and produces no fumes.

They process that batteries follow at this plant are the following:

- Batteries are placed in an assembly line where they are separated into modules.
- Metals and plastics from the casing are sent to conventional recycling.
- Modules are sent to shredding in a vacuum or inert atmosphere to prevent ignition even though cells are discharged. In order to power this process, they use the remaining energy in the battery modules.
- At this point, the liquid electrolyte is evaporated and condensed, and this way recovered. Using this innovative technique, they avoid the production of toxic fluorine compounds and solve the risk of possible ignition when discharging the cells.
- The granulated material from the shredding goes to a sorting system where the aluminium, copper and plastics from the separator film are extracted.
- The rest of the valuable materials are recovered by a hydrometallurgical process: nickel, cobalt, graphite, manganese and lithium with a high purity value, that allows it to be directly reused in new batteries.

They recycle around 96% of the materials using 70 % of less energy to handle the same amount of lithium-ion batteries in conventional methods as it does not require intensive heating. Moreover, it doesn’t create toxic products.

5.1.8 NICKELHÜTTE AUE

This German company offers a complete transport service according to ADR regulation and packaging solution for lithium batteries (GmbH, 2019).

They offer the possibility of recycling them by using pyrometallurgical or hydrometallurgical methods and with some of the materials recovered, they build materials for highways and roads.

6. Retrieval of batteries

The end of life recovery process has to begin with an effective collection of Li-ion batteries for which optimal retrieval mechanisms have to be taken into practice (Steward et al., 2019). This requires the auto industry and government regulatory agencies to develop adequate guidelines and policies for handling and transporting EV batteries (Ramoni & Zhang, 2013).

Until the moment, the collection of LIBs has been ruled by waste electrical and electronic equipment policies, as they were mainly used for consumer electronics. Nevertheless, it is likely that regulations affecting the recycling of vehicle batteries will be similar (Steward et al., 2019).

Nowadays, environmental regulations such as Directive 2000/53/EC on end of life vehicles of the EU, require the automakers to take extended responsibility for their vehicles and components after use. It assigns the responsibility of managing them at their end of life to the manufacturers. This requires that they collect their products with the aim of reusing, recycling or remanufacturing, or to delegate this responsibility to a third company (Ramoni & Zhang, 2013).

The transportation of the batteries to the recycling and repurposing facilities is a potential technical challenge, as they are classified as hazardous waste which makes transport expensive and highly regulated (Kelleher and Energy API, 2019). Furthermore, some studies have estimated this to be the dominant component of repurposing costs (J. Neubauer, K. Smith, E. Wood, 2015).

Batteries have to be shipped following certain guidelines, that is, packaged in rigid containers and in a manner to effectively prevent short circuits or violent rupture, allowing for the refurbishment facility to own and operate the vehicle used for transportation (J. Neubauer, K. Smith, E. Wood, 2015).

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

Batteries for reusing or recycling can be recovered from the certified dismantling centres where cars are disposed for dismantling.

They can arrive here by multiple ways (Casals, 2014):

- The owner can leave the car at the dealership that will later send the car to the treatment facility.
- The owner can bring it directly to the certified dismantling centre.
- Municipal services collect abandoned cars and bring them to the certified dismantling centres.

Another option is that batteries are collected from official car workshops.

Once they are at the certified dismantling centre, cars are dismantled, and their batteries are removed. It may also occur that cars cannot be dismantled at these facilities, so they have to be transported to a disassembly plant where they might be stored for a period of time before being disassembled (Steward et al., 2019).

7. Tests to determine the status of the batteries

As it has been mentioned before rechargeable batteries are considered to have failed when they can only be charged to 80% of their nominal capacity (Ramoni & Zhang, 2013). After that they can be reused for less demanding purposes.

However, unified guidelines or harmonized approaches for evaluating the batteries are needed to determine the state of health (SOH) of the battery and asses its capacity, voltage and operating performance level. Moreover, there isn't a clear definition of SOH and it is differently used over applications and manufacturers (Vanesa Ruiz et al., 2016).

Battery degradation is a combination of phenomena as gradual loss in reserve capacity and increase in internal resistance, which limits the power that can be extracted from the cell, causes additional heat to be generated and further reduces the terminal voltage (Grandjean, Groenewald, McGordon, Widanage, & Marco, 2018, Hossain et al., 2019).

Nevertheless, the degradation level depends on the materials used in the anode, cathode, electrolyte, separator or collector, the use of the battery and even on the fabrication process (Casals, Amante García, & Canal, 2019).

The identification of the battery status has to be fast, cheap and robust in order to provide a competitive advantage (Charles Robert Standridge & Hasan, 2015). Depending on these results, batteries can be classified for different final purposes.

Only two approaches concerning the establishment of rules to assess the battery status have been developed until now.

On the one hand, The Society of Automotive Engineers International is developing the standard SAE J2997 on battery secondary use and it will contain standards for testing and assessing batteries for a number of safe reuse possibilities (Charles Robert Standridge & Hasan, 2015).

On the other hand, it is also worth mentioning the standard ANSI/CAN/UL1974 even if it's only applicable in America, as it introduces new ideas such as the calendar expiration date. This information must be provided by the manufacturer and it sets a date from which the battery shouldn't be used any longer (Charles Robert Standridge & Hasan, 2015).

They also propose a list with some important data that a BMS should provide to understand the battery health.

This standard also prescribes a routine test analysis comprising:

- Incoming open circuit voltage measurement
- Incoming high voltage isolation check
- Capacity check
- Internal resistance check
- Check of BMS control and protection components
- Discharge/charge cycle test
- Self-discharge

Considering this lack of regulation, following the VDA initiative "Test specification for Li-ion battery systems" two main parameters have to be analysed: the capacity and the internal resistance.

7.1 Capacity

The basic method mainly used to measure the capacity is to fully charge or discharge the battery. The steps followed to perform these tests are described in Table 6.

Capacity test
Standard Cycle
Acclimatization at -25°C
Discharge 1C
Charge at cell nominal (C/3 normally)
Wait 30 min (for temp. stabilization)
Repeat 3 times charge/ discharge cycle
Acclimatization to RT
Discharge 10C
Charge at cell nominal (C/3 normally)
Wait 30 min (for temp. stabilization)
Repeat 3 times charge/ discharge cycle
Acclimatization to 40°C
Discharge 20C
Charge at cell nominal (C/3 normally)
Wait 30 min (for temp. stabilization)
Repeat 3 times charge/ discharge cycle
Acclimatization to RT
Standard charge

Table 6. Capacity test description according to VDA initiative

In order to completely perform these tests, following strictly all the steps described, it takes about 126,25 hours, which is not economically feasible.

7.2 Internal resistance

On the other hand, a pulse test needs to be performed in order to evaluate the internal resistance of the battery and the power losses in batteries. The steps followed in this case are enumerated in Table 7.

Power test
Acclimatization at 40°C
Standard cycle
Acclimatization at 40°C
Discharge 1C until 80% SOC
Acclimatization
Pulse:
Discharge at Imax for 18s
Relaxation for 40s
Charge at 0.75xImax for 10s
Relaxation for 40s
Discharge until next SOC step
Repeat for SOC 65,50,35,20 %
Standard charge 1C
Acclimatization at RT
Standard cycle
Repeat pulse test for all SOC steps
Acclimatization at -25°C

Standard cycle	
Repeat pulse test for all SOC steps	

Table 7. Power test description according to VDA initiative

Just like the capacity tests, if it is performed strictly it takes too much time (about 78,6 h) to complete this test.

7.3 Research in testing techniques

New test procedures have been investigated in the recent years. Some of them are supported by mathematical models like the Kalman filter and neural networks and others are empirical techniques manly based on capacity and impedance measurements. However, the first group are complex to develop and the second ones are highly dependent on the operating conditions (Quinard, Redondo-Iglesias, Pelissier, & Venet, 2019).

When it comes to the capacity fading assessment, the incremental capacity analysis has become a well-known technique and is gaining more credit in the battery community. It is a mathematical tool based on the variation of the electric charge inside the battery. The level of accuracy of the test is linked to the C-rate during the charge and discharge processes, the lower the C-rate the better the accuracy obtained (Quinard et al., 2019).

There are also numerous methods that are being studied for measuring internal resistance such as the application of multisine signals which quantifies the dynamic behaviour of LIBs and a new procedure known as pulse-multisine that combines a multisine and a pulse signal. Other techniques include energy methods and calorimeter based methods but they are time consuming and they do not offer any improved accuracy (Grandjean et al., 2018).

8. Options for the end of life of the battery

There is a wide range of possibilities for the second life of the battery. Before recycling them, they can be repurposed in a less demanding application.

This second use of the battery extends the total lifetime value of a battery up to 10 years by increasing economic revenue through second use alternative applications and decreasing the initial cost of battery (Neubauer, Pesaran, Williams, Ferry, & Eyer, 2012; Reid et al., 2016).

Figure 6 presents a flow diagram concerning the steps a battery will follow after its first life. Thus, the battery can be sent to remanufacture or directly to recycling and recover its materials.

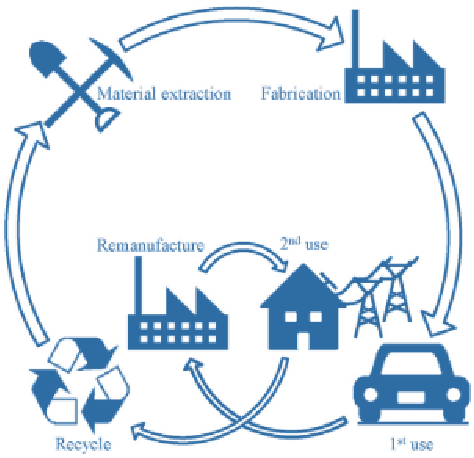

Figure 6. Circular economy model of lithium ion batteries. Source: Casals, Amante García, & Canal, 2019

8.1 Repurposing

Repurposing requires dismantling batteries into cells or modules and reassembling them into a different configuration than for a vehicle (Charles R Standridge et al., 2014) .

Dismantling is a critical process due to the weights and high voltages of batteries that needs to be done by qualified employees (Pistoia & Liaw, 2018). Till the moment, this process has been done manually, however the robotic disassembly has been a research focus in the last years. The automation of dismantling could eliminate the risk of harm to human workers and reduce costs apart from improving the mechanical separation of materials and components (Harper et al., 2019).

Another challenge that we face today is that since there are no cell standards, each manufacturer has a different cell type and they require different module types. All these aspects makes it more difficult to mix and match battery modules into second use applications (Warner & Warner, 2015).

Many pack manufacturers also weld the cells into the modules which means that it is nearly impossible to replace cells in a welded module, so the whole module must be either used or recycled (Warner & Warner, 2015; Sonoc, Jeswiet, & Soo, 2015).

When replacing cells, it must be considered that the final pack will be limited by the lowest capacity cell, therefore the cells or modules must be closely matched in capacity and voltage. This issue could be solved with an active balance of batteries, but this solution would increase the total cost of the procedure. Another requirement is matching cells or modules based on some aging criteria. In the same way that a lower capacity cell will lower the final capacity of a pack, a more aged cell or module will limit the life of the newly built pack (Warner & Warner, 2015).

In this case, also some maintenance procedures and changes in the battery may be required like adapt the BMU to the new application, repairing damaged material, adding electrical hardware and control and safety systems (Ll Canals Casals & Amante García, 2016; Cready et al., 2003). Moreover, each application may need a particular configuration of the battery (Charles R Standridge et al., 2014).

It seems clear that this strategy requires more time and work and some elements will have to be replaced which increases the final cost. Nevertheless, the repurposed battery offers a much more flexible, optimized and fitted functional final unit (Ll Canals Casals & Amante García, 2016).

8.2 Direct reutilization

In this case, there's no need of disassembly and the battery will be directly transferred into a new application after the appropriate tests are performed and minimum adaptations for its second life are accomplished (Lluc Canals Casals, Amante García, & Cremades, 2017).

This is the cheapest and fastest option and previous studies agreed that this strategy may present selling prices below 100 $/kWh (Ll Canals Casals & Amante García, 2016 ,Casals, 2014).

Nevertheless, it also presents several complications. On the one hand, repurposing plants are not able to access the data contained in the BMS, which could provide them a reference of the capacity and the battery status and could be compared with the results of the tests (Grandjean et al., 2018). Instead, they have to handle the battery without this information which is not an easy task.

At the same time, as operations in the battery are minimum, they are not suitable for many applications, so its final use is more restrictive.

As a summary, the main advantages and disadvantages of both reuse strategies are described in Table 8.

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

Table 8. Pros and cons of the direct re-use and module reconfiguration strategies. Source:(Casals, 2014)

8.3 Recycling

Batteries that are no longer able to support any application must be recycled and materials such as lithium, cobalt, nickel, copper, steel and plastics can be retrieved (Attias, 2016; Charles Robert Standridge & Hasan, 2015).

One of the challenges with recycling lithium-ion batteries is that it is very energy intensive to get the precious metals out of the cells and often uses more energy that can be recovered during the recycling process. In addition, the value of the materials that are recovered sometimes does not cover the cost of the recycling process (Warner & Warner, 2015).

However, several efficient methods for recycling have been developed lately as explained in previous section 5.1.

9. Recovery and recycling plant design

After analysing the current state of battery reusing and recycling, the creation of a business that will collect discarded batteries from EVs and either repurpose or recycle them will be proposed in the following chapters.

9.1 Location of the plant

The selection of the location is a decisive economic factor, especially with regard to the collection of batteries. The transport routes to the treatment facilities have to be kept as short as possible to avoid costly transport considering batteries are classified as dangerous goods and are subject to high safety requirements (Hoyer, Kieckhäfer, & Spengler, 2015).

In order to define the most optimal location for the plant defined in this project, several economic, environmental and social factors will be analysed.

The proposed countries for establishing the industry are Norway, Germany, UK, France, Sweden, Netherlands and Spain. These are the top sales countries in Europe, and they all experimented a positive growth in sales compared with data from the previous year. In Table 9 the number of EV sales in the mentioned countries are shown.

Country	EV sales in units (thousands)
Norway	77
Germany	74
UK	62
France	52
Sweden	29
Netherlands	28
Spain	13

Table 9. EV sales in 2018 in the selected countries. Source:(EV-Volumes, 2019)

For each possible location the factors described below will be analysed.

Charging infrastructure

The widespread of recharging points is a key factor for the development of electromobility (EEA, 2016; Yong & Park, 2017). In Table 10 the number of publicly accessible charging points in Europe for each alternative country are presented.

Country	Charging points (units)
Norway	10350
Germany	10878
UK	14256
France	123639
Sweden	4733
Netherlands	32875
Spain	4974

Table 10.Number of charging points in the selected countries. Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

Recycling infrastructure

The existence of a consolidated recycling infrastructure can be a determinant factor for the success of the proposed plant.

The Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 requires Member States to ensure that appropriate collection schemes are in place for waste portable batteries and sets a target for the collection rates of 25% in weight of the amount placed on the market by 2012 and 45% by 2016. It also requires Member States to set up collection schemes for waste automotive batteries (European Commission, 2019a)

According to statistics from the European Commission the rates achieved in each of the alternative countries by 2016 are the ones seen in Table 11.

Country	Collection rate (%)
Norway	51
Germany	46,2
UK	44
France	44,5
Sweden	45,1

Netherlands	49
Spain	38,2

Table 11.Collection rates in the selected countries. Source: (European Commission, 2019a)

Clean energy

EVs have to be powered using energy from renewable sources, otherwise, the opportunity they offer of reducing our dependence on fossil fuels and the emissions of greenhouse gases will be wasted (Cusenza, Bobba, Ardente, Cellura, & Di Persio, 2019; Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014).

Table 12 provides and overview of the share of total production of renewables energies by 2017 in the selected countries.

Country	Clean energy share (%)
Norway	6,6
Germany	36,8
UK	13,2
France	19,6
Sweden	53
Netherlands	13,4
Spain	51,3

Table 12. Clean energy production share in the selected countries. Source: (Eurostat, 2019)

Government Incentives

The governments active policy support is a major factor for the widespread adoption of EVs. Thereby, countries that promote electric vehicles are providing policy support such as purchase subsidies, public expenditure, tax reduction, tax exemption, free charging and parking permissions (Yong & Park, 2017).

Table 13 gives an overview of the incentives for electromobility and charging infrastructure provided in the selected countries by 2017. These include bonus payments to encourage the purchase of EVs, reductions in registration and annual circulation taxes or even exceptions for new vehicles, local incentives and investment in charging infrastructure.

Country	Bonus payments and premiums	Tax benefits	Local incentives	Charging infrastructure incentives
Norway	x	x	x	x
Germany	x	x	x	x
UK	x	x	x	x
France	x	x	x	x
Sweden	x	x		
Netherlands		x	x	x
Spain	x	x	x	x

Table 13.Comparison of the selected countries incentives for EVs. Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

Corporation tax

When it comes to the economic variables affecting the location of the plant, the corporation tax is one of the main taxes a business must pay.

The current rate for each of the selected countries are shown in Table 14.

Country	Corporation tax (%)
Norway	22
Germany	30
UK	19
France	31
Sweden	21,4
Netherlands	19
Spain	25

Table 14. Corporation tax in the selected countries. Source: (European Union, 2019)

Workforce average price

The workforce costs are an important part of any business expenses, therefore, its average price (including wages and salary and other additional costs) in each of the selected countries will be evaluated for the final selection of the plant and are shown in Table 15.

Country	Average price (€/h)
Norway	50
Germany	34,6
UK	27,4
France	35,8
Sweden	36,6
Netherlands	35,9
Spain	21,4

Table 15. Workforce average price in the selected countries. Source:(eurostat, 2017)

Once we have defined a list of possible locations for the plant and the external factors that will be analysed, a weight is assigned to each factor in order to prioritise them, according to the influence they will have on the final choice. These weights are provided in Table 16.

Factor	Weight (%)
Sales	40
Charging infrastructure	30
Recycling rates	15
Clean energy	30
Government incentives	25
Corporation tax	5
Workforce average price	10

Table 16. Weight for each decision factor. Source: own elaboration

Given the values in Tables from 9 to 15, the normalized values for each factor of decision are shown in Table 17.

Note that these values have been scaled from 1 to 5 in order to avoid working with very low numbers.

	Alternatives							
	Norway	**Germany**	**UK**	**France**	**Sweden**	**Netherlands**	**Spain**	**Weight (%)**
1. Sales	5,00	4,81	4,06	3,44	2,00	1,94	1,00	40
2. Charging infrastructure	1,19	1,21	1,32	5,00	1,00	1,95	1,01	30
3. Recycling rates	5,00	3,50	2,81	2,97	3,16	4,38	1,00	15
4. Clean energy	1,00	3,60	1,57	2,12	5,00	1,59	4,85	30
5. Government incentives	5,00	5,00	5,00	5,00	1,00	3,00	5,00	25
6. Corporation tax	4,00	1,33	5,00	1,00	4,20	5,00	3,00	5
7. Workforce average price	1,00	3,15	4,16	2,99	2,87	2,97	5,00	10

Table 17. Scaled values for each alternative. Source: own elaboration

Finally, the technical weighed value (Işiklar & Büyüközkan, 2007) for each alternative is provided in Table 18.

Technical weighed value						
Norway	**Germany**	UK	France	Sweden	Netherlands	Spain
0,6395724	**0,7015891**	0,6058941	0,6886410	0,4790974	0,45831007	0,54208721

Table 18. VTP for each alternative. Source: own elaboration

The optimal solution in this case is Germany, as it is the one that satisfies the most the assessment criteria chosen according to the followed method. See Appendix 1 for a more detailed description and analysis of the location chosen.

It must be noted that the plant will only be able to repurpose some specific models of batteries because as it has been explained before, batteries from different car manufacturers and even from different models of the same brand, present several differences. In this project, we are going to choose the two most sold EV models in Germany in 2018, which are the Renault Zoe and the Volkswagen e-Golf. The number of units sold for each one can be checked in Table 19.

Model	**Sales (units)**
Renault ZOE	6360
Volkswagen e-Golf	5743

Table 19. Best-selling EV models in Germany in 2018. Source: (Kraftfahrt-Bundesamt, 2018)

The technical specifications of both battery models are summarised in Table 20.

Parameter	Renault ZOE	Volkswagen e-Golf
Capacity	52 kWh	32 kWh
Voltage	400 V	323 V
Number of modules	10	27
Number of cells	192	264
Weight	326 kg	318 kg

Table 20. Renault ZOE and Volkswagen e-Golf battery's specification. Source:(Kane, 2019; Pearl, 2019; "Smart EQ forfour price and specifications - EV Database," 2020)

To define the final location of the plant in Germany, the presence of other recycling plants and car manufacturers will be evaluated. In Figure 7 we can observe the location of Volkswagen manufacturing plants and the recycling plants mentioned in previous Section 4.

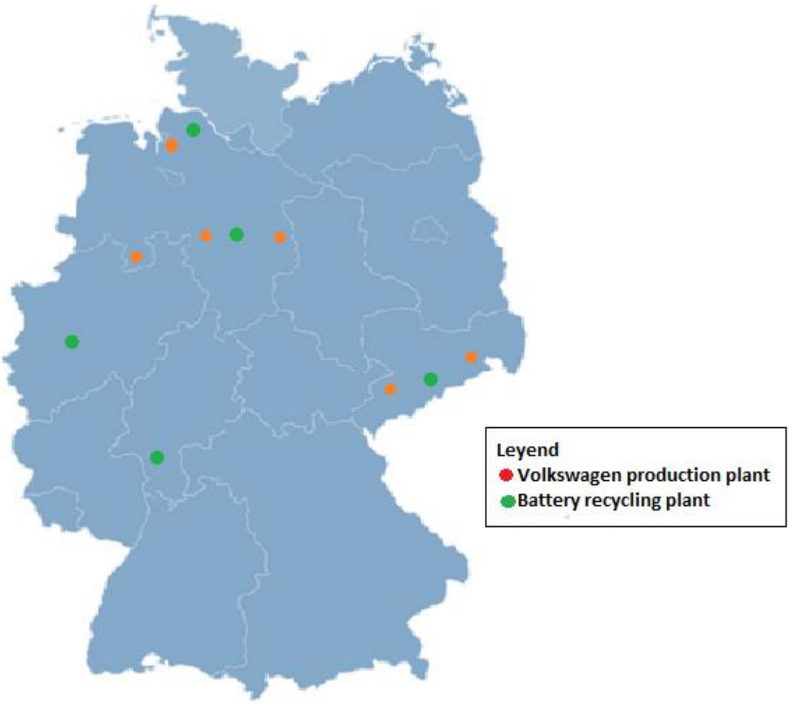

Figure 7. Location of recycling plants and Volkswagen production plants in Germany. Source: own elaboration

As it can be seen in previous figure, most plants are located in the half northern of the country, and some recycling plants are close to the production centres.

Lower Saxony could be a good site for the proposed plant in this project as it is the one with the highest number of Volkswagen production plants. However, there are already two plants in the surroundings that recycle lithium ion batteries and Volkswagen has set up a plant in the area that will start running this year and will also repurpose batteries to give them a second life (Volkswagen AG, 2019).

Concerning the high competency in this state, Saxony could be another suitable alternative. In this region, there are also two Volkswagen production plants and only one recycling plant. This company (Nickelhütte Aue) provides battery collection and recycling, but they don't offer the possibility of reconfiguring batteries and giving them a second life. Therefore, the proposed business in this project could take advantage of this issue and establish in the area.

9.2 Forecast of the number of batteries

Concerning the Renault ZOE and the Volkswagen e-Golf, they both have a battery guarantee of 8 years (“2020 VW e-Golf | All-Electric Car | Volkswagen,” 2019; “New ZOE - Driving Range, Battery & Charging - Renault UK,” 2019), so on the basis of the sales data of 2015, we can suppose the plant will start running in 2023.

In Table 21 we can check the sales from 2015 to 2018 of both mentioned EV models. These data reflects an exponential increase in the number of sales and the forecasts for future years also predict an important growing (Energy Agency, 2019; The International Renewable Energy Agency, 2019).

Model	**2015**	**2016**	**2017**	**2018**
Renault ZOE	1787	2805	4657	6360
Volkswagen Golf	1092	1989	2696	5743
Total	2879	4794	7353	12103

Table 21. Sales in Germany for the Renault ZOE and Volkswagen e-Golf. Source: (EV-Volumes, 2019; Kraftfahrt-Bundesamt, 2018)

Based on these data, the amount of EVs that can arrive to the plant from 2023 is presented in Table 22. According to the statistics of collection rates of portable batteries presented by the European Union in 2016, Germany presents a collection rate of 46,2 %. Bearing in mind the incentives carried in the recent years to recycle and recover battery materials it is not unreasonable to consider that 50% of sold batteries will arrive to the plant.

Model	**2023**	**2024**	**2025**	**2026**
Renault ZOE	894	1403	2329	3180
Volkswagen Golf	546	995	1348	2872
Total	1440	2397	3677	6052

Table 22. Expected input in the plant. Source: own elaboration

Given that the vehicle fleet in Germany is 45.803,560 (ACEA, 2018) and the total number of traffic road accidents in Germany in 2018 was 2.636.468 (Destatis, 2020), which represents around 5%, we are going to suppose this is the rate of batteries that will be directly recycled. The remaining 95 % will be either repurposed or directly reused.

The main advantages of disadvantages of both second-life strategies were detailed in previous sections 8.1 and 8.2. The direct re-use solution is the most optimal from an economic point of view, however it is more realistic to plan that most batteries will need to go through some reconfiguration process, considering that few applications will require such high capacity batteries and in most cases, they will need to be adapted to its new use. Therefore, we have estimated that 60% of batteries will be repurposed and 35% directly re-used. Considering these percentages, the input of the plant for the year 2023 is shown in Table 23.

Model	Annual input (units)		
	Direct reuse	Repurpose	Recycle
Renault ZOE	313	536	45
Volkswagen Golf	191	328	27
Total	504	864	72

Table 23. Annual input of the plant in the year 2023. Source: own elaboration

9.3 Optimization for battery retrieval

As lithium ion batteries are considered a hazardous material, the shipping costs are a key component of battery repurposing and recycling costs.

The recovery and recycling plant will offer a collection service and batteries will be picked-up from certified dismantling centres as explained in Section 6, considering distances of maximum 250 km.

In order to optimize this process a simulation model was built.

The steps for the retrieval are described below:

- When a certified dismantling centre has a battery to be collected, a notification is sent to the plant.
- The truck that will collect the batteries has a capacity of five batteries. Therefore, in order to optimize each trip, batteries will only be collected when the truck can be filled, that is, when there are five batteries available in the same dismantling centre.
- If the truck is available, it goes immediately to the dismantling centre.
- Once the truck has arrived, there is a time for packaging and loading the battery.
- Once the truck is full it goes back to the plant.
- Finally, batteries are unloaded in the plant by the forklift.

The times estimated for each operation are shown in Table 24.

Operation	Time	Resource
Arrival of batteries to be collected	2h	
Waiting time for available truck	Triangular (30,60,120) min	Truck
Trip from plant to certified dismantling centre	Triangular (1,2.5,4) h	Truck
Loading batteries	10 min	Truck
Trip from certified dismantling centre to plant	Triangular (1,2.5,5) h	Truck
Unloading batteries in plant	15 min	Forklift

Table 24. Time considered for each operation in the collection process. Source: own elaboration

The simulation model built is illustrated in Figure 8.

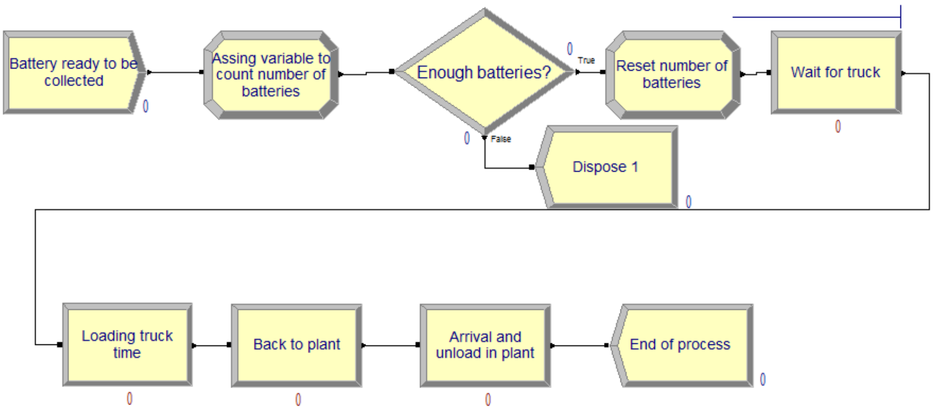

Figure 8. Simulation model. Source: own elaboration

The simulation was set for a period of 5 days and 8 hours per day and in this time a total of 4 full trucks, that is 20 batteries, arrived at the plant. This input is accurate considering the number of batteries that are estimated to arrive at the plant for the first year of operation according to Table 23.

To complete this simulation, it will be considered the pollution when transporting the batteries, given that the emission factor of a diesel truck is 2,61 kg of CO_2 /litter (Oficina Catalana del Canvi Climàtic, 2011) and the average consumption is 30 litters per 100 km. That means that for every trip of 100 km 78,3 kg of CO_2 will be released to the atmosphere. These data underline the importance of optimizing each trip to the maximum and it justifies the fact that the collection trip will only start once it is assured that the truck will be full.

On the other hand, the specific cost rate for the retrieval is 3 €/kWh (Rohr, Wagner, Baumann, Muller, & Lienkamp, 2017). For the simulation built, considering a total of 20 batteries collected with a total capacity of 52 kWh, the total cost computed is 3120€. The total costs for the retrieval in the proposed plant are evaluated in Chapter 10.

9.4 Plant layout

The battery collection and repurposing for a second life plant will be divided in three main areas:

- The repurposing area
- The recycling facilities
- The administrative area

In the repurposing area batteries are received and unloaded by a forklift. If necessary, they will be stored in racks. Otherwise, batteries are taken to the inspection area where the battery status is visually checked and then they are prepared to be tested in testing stations.

Tests will be performed according to the VDA initiative presented in previous Tables 6 and 7. However, a total improved testing time of 24 hours will be consider as it is not feasible for any business to run the timings proposed (Casals, 2014).

They will be tested using a full featured battery testing system specially designed for automotive batteries. These stations are able to perform charge and discharge cycles of batteries or modules to obtain charge and discharge capacity, energy and internal resistance. The acclimatization to the temperatures required for the tests will be done in climate chambers.

Once these tests are finished, the technicians will disconnect and classify them according to test results. In case it is decided to directly reuse the batteries, they will go through some maintenance operations and they will be tested again.

On the other hand, batteries that are going to be used for a new purpose will be manually dismantled into modules and reassembled into a new configuration. This will require some maintenance tasks and changes in the battery. Also, damaged material will have to be replaced by new components.

Finally, the batteries are stored in the racks before being shipped. The storage time should be as less as possible, otherwise batteries would need to go through an additional testing and being recharged if necessary.

The time distribution for each strategy is shown in Table 25.

Direct re-use		**Repurposing**	
Process	**Time (h)**	**Process**	**Time (h)**
Physical inspection	0.5	Physical inspection	0.5
Test preparations	1	Test preparations	1
Battery test	24	Battery test	24
Disconnection and battery classification	0.5	Disconnection and battery classification	0.5
		Dismounting in modules	9
Interface mounting and maintenance	1	Battery rehabilitation	9
Final testing	0.5	Final testing	0.5
Storage	0.25	Storage	0.25
Shipping	0.5	Shipping	0.5

Table 25. Time distribution for the direct re-use and repurposing strategies. Source: (Casals, 2014)

If batteries are not suitable for being given a second life, they will be recycled following the next process:

- They are placed in an assembly line where they are discharged and dismantled into modules.
- Metals and plastics from the cashing are separated and sent to conventional recycling.
- Modules are sent to the shredding machine using a conveyor. This process will take place in an inert atmosphere to prevent ignition. The granulated material obtained will be kept in plastic bags.
- Once the granulated material has left the shredder the liquid electrolyte is evaporated and condensed to be recovered. This liquid is contented in a tank and when it is full is taken by the forklift and can be reused in another industries.
- The granulated material obtained goes through a sorting system in which the aluminium, copper and plastics from the separator are extracted. It passes through a screening, a magnetic separator and a cyclone filter.
- The rest of the material, which has been turned into dust, is taken to the laboratory and recovered there by a hydrometallurgical process. The process is described in Figure 5.
- It starts with a fines leaching by adding lithium hydroxide(aq) which produces an alkaline solution of lithium salts and a suspension of metallic oxides and carbon.

- On the one hand the alkaline solution is precipitated by adding carbon dioxide and Li_2CO_3 is obtained. Next, it is washed and dried in a chamber at 105ºC.
- On the other hand, the suspension of metallic oxides and carbon is dissolved in H_2SO_4. Then, it goes through a purification and oxidation process to recover cobalt and the remain lithium, which is sent back to the precipitation stage.

It must be taken into consideration the energy consumption required to perform the recycling activity which is around 0,14 kWh per every kilo of battery treated (Domingo, 2016). Furthermore, the use of chemical substances such us sulfuric acid and other inorganic chemical and the generation of waste products and sewage water are other important impacts derived from the recycling process.

Also, the recycling cost is considerably high, around $2,25 per pound (Foster, Isely, Standridge, & Hasan, 2014). Taking the example of the Renault ZOE battery, with a weight of 326 kg, the cost for recycling the full battery would be 1487,72 € which can be translated into 28,61 €/kWh.

Moreover, in this case the main benefits will come from selling the materials obtained which are cobalt, lithium, nickel, graphite, manganese, metals and plastics from the cashing, the liquid electrolyte, aluminium, copper and plastics from the separator. However, these earnings are quite difficult to compute, as material prices vary constantly according to market stock.

All these concerns, apart from the already stablished recycling companies in the area and the low percentage of batteries that are expected to be directly sent to recycling, lead us to the conclusion that it is not worth it to create another recycling plant in the area. That is, the plant proposed in this document will only collect batteries to either repurpose or directly re-use them and in case that a damage battery arrives to the plant, it will be stored in a small warehouse next to the repurposing facilities to be sent to a recycling company.

Eventually the administrative area will be compound of the following units:

- Offices for the plant manager, the maintenance engineer and the administrative assistant.
- Breakroom for workers.
- A Workshop for repairing any equipment or machine and for maintenance tasks.
- Toilets.

Bearing in mind that the plant proposed in this document will recover batteries to refurbish them, a sample floor plan is shown in Figure 9.

Figure 9. Battery collection and repurposing for a second life plant layout. Source: own elaboration

10. Economic evaluation

In this chapter the economic feasibility of reusing and recycling discarded batteries form EVs is evaluated. The costs involved in the mentioned strategies can be broken down into various components such as transportation, packaging, testing, labour, materials, energy or facilities among others.

Transportation costs

For the transportation costs we are going to assume batteries will be collected in a regional area, supposing distances within 250 km. Then, the specific cost rate for the retrieval is 3 €/kWh (Rohr, Wagner, Baumann, Muller, & Lienkamp, 2017). Bearing in mind the capacity of the Renault ZOE battery, the total cost for one of these batteries would be 156€, which represents 0,48€/kg. Meanwhile the packaging costs are considered to be 38€ per battery (Casals, 2014).

Material costs

In case of choosing the repurposing strategy, it must also be considered the materials costs, as the new battery will require interconnects, cooling components, electronics and the package in which the modules are assembled. These components were estimated to cost about 250$ per battery pack (Cready et al., 2003).

Labour costs

The number of employees required to operate the facility was determined considering the daily input of the plant, the estimated percentage of batteries that will be directly reused, repurposed or recycled and the time requirements for each solution.

The facility will employ four technicians, a plant manager, an administrative assistant that will provide support to this last one, an electrical engineer to maintain the test equipment, a truck driver and a forklift driver.

Estimates for the hourly wages for each of these employees are presented in Table 26.

Workers	Annual salary
Forklift driver	30.744,00 €
Truck driver	30.744,00 €
Manager	69.600,00 €
Electrical engineer	64.356,00 €
Administrative assistant	43.044,00 €
Technician	58.500,00 €

Table 26. Workers' wages. Source:(Bundesagentur für Arbeit, 2018)

Rent

The estimated surface of the recovery area will be around 774 m^2 and the administrative area 129 m^2. According to internet review we are going to consider an average rent cost of 3€/month/m^2.

Energetic costs

The energetic costs have been estimated using the following expression: actual price of kWh x 1.5 x annual throughput + 2.25$/ m^2 (Neubauer et al., 2012).

Other direct costs

Other direct costs were considered as 2% of labour costs (Cready et al., 2003). This include phone, office supplies and other costs of doing business.

Indirect costs

As indirect costs we are going to include general and administrative expenses, warranty and insurance expenses. They can be estimated as 16%, 4% and 3% of total direct costs, respectively (Cready et al., 2003).

Used batteries buying price

The automotive battery owner will be paid by the recovery and recycling company for the used battery. The costs considered are 24$/kWh (J. Neubauer, K. Smith, E. Wood, 2015).

10.1 Results for the direct re-use and repurposing strategies

The cost of directly reusing and repurposing EV batteries are summarized in Tables 27 and 28. For these calculations we have considered all the variables described in previous section for the scenario of year 2023 presented in Table 23.

Concept	Annual expenses (€)
Transportation	86.276,05 €
Labour	158.664,96 €
Energy costs	841,65 €
Rent	13.653,36 €
Other direct costs (2% labour)	3.173,30 €
Total direct costs	262.609,32 €
Insurance	7.878,28 €
G&A	42.017,49 €
Warranty	10.504,37 €
Total	323.009,46 €
Cost per battery	641,11 €
Cost per kWh	**15,26 €**

Table 27. Cost per kWh for the direct reuse strategy. Source: own elaboration

Concept	Annual expenses (€)
Transportation	147.901,80 €
Labour	313.823,04 €
Energy costs	1.189,99 €
Materials	195.196,20 €
Rent	18.854,64 €
Other direct costs (2% labour)	6.276,46 €
Total direct costs	683.242,13 €
Insurance	20.497,26 €
G&A	109.318,74 €
Warranty	27.329,69 €
Total	840.387,82 €
Cost per battery	973,01 €
Cost per kWh	**23,17 €**

Table 28. Cost per kWh for the repurposing strategy. Source: own elaboration

From these results we can confirm the direct reuse strategy is the most attractive from an economic point of view mainly due to avoiding replacement materials costs and a reduction in labour costs.

However, to these costs we have to add the price the plant will pay to the battery owner which will be considered 24$/kWh (21,80 € according to the exchange rate of the day 11th of March of 2020). Given that, the total cost of repurposing and reusing the battery are 44,97€ and 37,06€, respectively.

If we consider batteries will be sold at a price of 50$/kWh(J. Neubauer, K. Smith, E. Wood, 2015) (45,42€ given the exchange rate of the day 11th of March of 2020) the margin profit will be of 0,45€/kWh and 8,36 €/kWh for the repurposing and reusing strategies respectively.

We can conclude the benefit margin is really tight. Nevertheless, the profits will increase in the following years, as the input of batteries will be higher, and this will contribute to reduce battery prices.

If we analyse the year 2026, the number of batteries arriving to the plant is estimated in 11498 units (without considering the 5% of batteries that will be recycled), according to 2018 sales (see Table 21). Then, if we compute the kWh price for each solution, the values obtained are considerably lower.

In tables 29 and 30, it can be checked that prices have fallen from 15,26 € to 6,07€ for the first strategy and from 23,17€ to 12,84 € for the second one for the year 2026.

Note that for these calculations the same base prices as previously described in section 10 have been taken into account, adjusting the labour and space floor requirements for the expected input in the plant. Also, it must be mentioned that it has been assumed that the collection rate of batteries is 100%.

Concept	Annual expenses (€)
Transportation	701.190,70 €
Labour	158.664,96 €
Energy costs	1.093,75 €
Rent	13.653,36 €
Other direct costs (2% labour)	3.173,30 €
Total direct costs	877.776,07 €
Insurance	26.333,28 €
G&A	140.444,17 €
Warranty	35.111,04 €
Total	1.079.664,56 €
Cost per battery	254,88 €
Cost per kWh	**6,07 €**

Table 29. Cost per kWh for the direct reuse strategy. Source: own elaboration

Concept	Annual expenses (€)
Transportation	1.202.041,20 €
Labour	313.823,04 €
Energy costs	1.743,40 €
Materials	1.641.166,80 €
Rent	18.854,64 €
Other direct costs (2% labour)	6.276,46 €
Total direct costs	3.183.905,54 €
Insurance	95.517,17 €
G&A	509.424,89 €
Warranty	127.356,22 €
Total	3.916.203,81 €
Cost per battery	539,29 €
Cost per kWh	**12,84 €**

Table 30. Cost per kWh for the repurpose strategy. Source: own elaboration

11. Second life applications

There are thousands of applications where batteries are required as they can provide many different services.

Some of the most commons revenue streams available in Europe are shown in Figure 10.

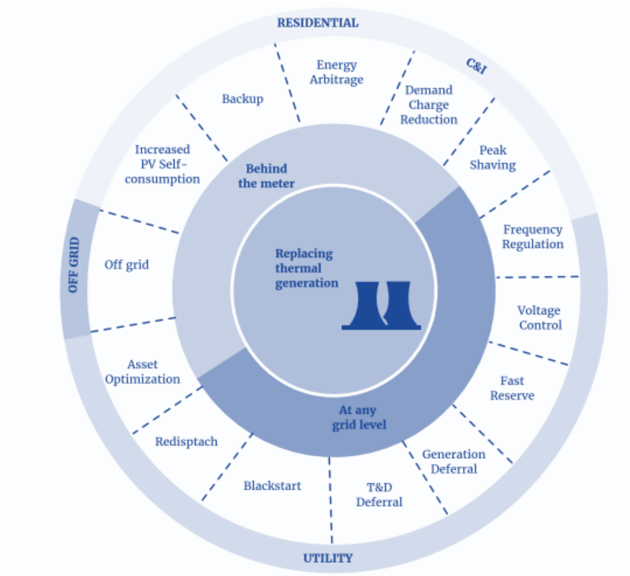

Figure 10. Most common battery services to different stakeholders. Source: (Reid et al., 2016)

As it can be seen in the graph, they can be used at different levels: residential, commercial and industrial, providing support to the transmission and distribution grid or in renewable power plants and thermal generation (Reid et al., 2016). Some of the main applications will be detailed below.

Off grid applications

There are still about millions of people living without electricity and regions where grid connection is highly unstable. A typical system employed in these cases consists of a 50-watt solar panel and a lithium-ion bases battery capable of powering lights and small appliances for a few hours in a 12-volt DC system. This combination is cheap and quick to build and provides reliability for isolated regions (Reid et al., 2016; Richter, Rehme, & Temmler, 2016).

Australia and Hawaii are the first cases and good examples of this evolution that will affect other locations and regions as the economics of batteries and renewables improves. That is, we are moving from a centralised model built around fossil fuels to a decentralised model where communities use micro grids to satisfy their own power needs (Reid et al., 2016).

Factories and commercial buildings

The adoption of batteries will help companies to reduce their energy costs through peak shaving, price arbitrage as well as providing backup power (Richter et al., 2016).

Transmission and distribution grid

Batteries can provide ancillary services to the grid to facilitate flexible generation and demand and for the deferral to transformers and other transmission and distribution assets by meeting the peak demand with storage power at lower demand times(Lacey, Putrus, & Salim, 2013).

In the future, it is expected that there will be storage at every voltage level within electricity networks as it is illustrated in Figure 11.

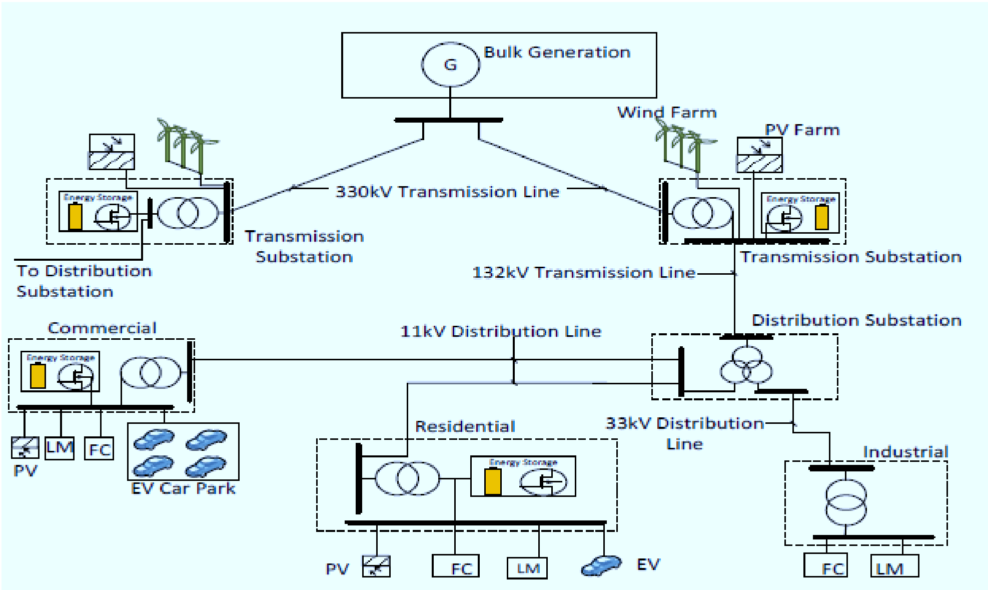

Figure 11. A vision of future distribution networks. Source: (Lacey et al., 2013)

Renewable power plants

Coupling batteries with renewables energies solves the problem of intermittency and grid stability with these sources. Batteries allow renewables to store the excess power when it is produced for a later dispatch when it is needed and they are able to compensate in real time the high variability (Saez-de-ibarra, Martinez-laserna, Stroe, Swierczynski, & Rodriguez, 2016).

Thermal generation

Batteries will allow conventional power plants generate more revenues on the balancing market while increasing their flexibility. Moreover, they give conventional power plants the ability to restart the grid in case of a blackout (Reid et al., 2016).

In the next sections, four possible second life applications will be assessed from a technical, economic, environmental and social point of view, considering the concept of a sustainable business model.

Also referred to as business models towards sustainability, it implies integrating the basis of sustainable development into the core of conventional business model modifying it by creating economic, social and environmental value (Geissdoerfer, Bocken, & Hultink, 2016; Geissdoerfer, Savaget, Bocken, & Hultink, 2017) .

11.1 Residential and commercial energy storage applications

Batteries can be used in grid-connected residential and commercial systems for time of use energy cost management, demand-charge management, service reliability and also for renewable integration. They will bring lots of benefits like reducing energy losses and making it possible for homes and businesses to manage their own power consumption based on pricing and their own-time-of-day energy necessities (Heymans, Walker, Young, & Fowler, 2014).

In addition to grid-connected stationary storage systems, traction batteries are also attractive for application in off-grids storages, especially for areas where the grid connection is unreliable.

They are used for optimizing the own consumption of electrical energy from photovoltaics. By coupling the photovoltaic systems with battery storages, excess energy can be buffered and used in peak respectively during periods of reduced solar radiation (Richter et al., 2016).

Stationary storage systems in on-grid solutions serve, among other things, to stabilize the electricity grid (Richter et al., 2016). Matching power generation and demand is a hard task due to the uncertainty over renewable generation and changing consumer profiles. Consequently, there is a considerable variation between peak hours, which lasts just a few hours for the daily cycle (around 4 hours) and valley ones. This phenomenon makes it mandatory for utilities to design transmission and distribution systems sized for peak load requirements, what means that the network is under loaded most of the time (Heymans et al., 2014; Lacey et al., 2013).

The time of use management, also known as peak shaving, has been boosted with the entrance on the market of time of use tariffs (TOU). TOU rates are generally structure as peak, partial-peak and o -peak time periods, and they offer economic advantages for both the customer and the producer (Reid et al., 2016).

Energy storage can be configured to pre-charging during off-peak hours and discharging to meet customer load during peak periods. Furthermore, an energy storage system used for TOU bill management will be idle for a large portion of the day and therefore available to collect revenue from other grid services (Reid et al., 2016). It must be considered that in order to maximize the customer savings, the charging and discharging periods of the battery must coincide with the times of lowest and highest energy pricing, respectively (Heymans et al., 2014).

Furthermore, if this system is coupled with solar energy its performance can be improved (Reid et al., 2016). These installations are compound of PV panels, the battery modules, a battery charge controller that limits the rate at which electric current is added to or drawn from the batteries, and a DC/AC inverter. A schematic can be checked in Figure 12.

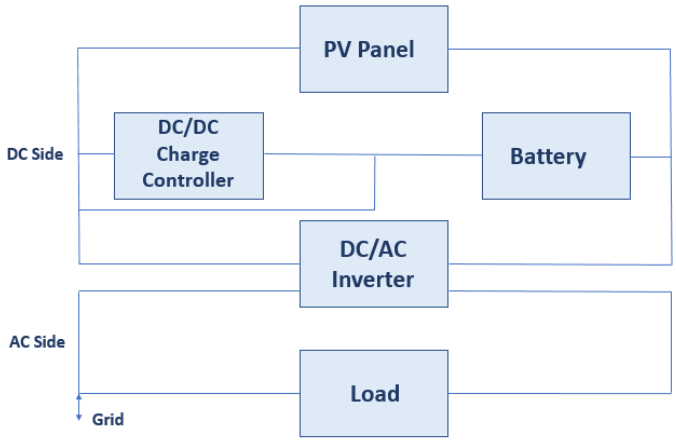

Figure 12. PV/battery system schematic. Source: (Burke, 2009)

The voltage of the DC side of the residential systems is in the range of 24-150 V and that of large commercial systems in the range of 500-600 V. The peak power of the residential systems is 3-5 kW and that of the commercial is around 100-200 kW (Burke, 2009).

They can also be implemented for industrial applications, for load levelling the demand, which is much higher, around 100000 kWh (Hossain et al., 2019).

At first instance, the only barrier for the implementation of the systems described above is the demonstration of their economic feasibility (Burke, 2009). Several studies state that by increasing the total lifetime value of the battery extracting additional services and revenue from the battery in a post-vehicle application, the overall cost of energy storage solutions for both the primary (automotive) and secondary (grid) customer would be decreased (Heymans et al., 2014; Neubauer et al., 2012; Williams & Lipman, 2010) and thus they can create significant monetary value (Beer et al., 2012).

In the same line, the longer the second-use service of a used battery pack is elongated, the higher net profits can be earned (Lih, Yen, Shieh, & Liao, 2012)

The benchmark costs of Li-ion stationary storage systems in 2017 were about 750 €/kWh for residential batteries. Ultimately, by 2040, stationary storage systems costs will range between 250 and 365 €/kWh for households (European Commission, 2018).

In a study carried by the Sandia National Laboratories in USA in 2010 the maximum and minimum expected benefits for a lifecycle of 10 years, considering an inflation of 2’5% and a 10% discount rate where estimated and are presented in Table 31. From the results obtained it can be seen the time of use energy cost management is the application that provides the highest benefits.

Application	Benefit (low) $/kWh	Benefit (high) $/kWh
Time of use energy cost management	1226	1226
Demand charge management	582	582
Electric service reliability	359	978
Renewables energy time shift	233	389
Renewables capacity firming	709	915

Table 31. Benefits of energy storage applications. Source: (Eyer & Corey, 2010)

From an environmental point of view the second use of an EV battery for energy storage would extend the use of the metal and other raw material resources manufactured into the battery cells and improve the life cycle material (Walker, Young, & Fowler, 2015). It must be noted that battery production represents between 30%-50% of an EV total lifetime greenhouse gases emissions (Dunn, Gaines, Sullivan, & Wang, 2012; J. Sullivan, 2010).

These environmental benefits can be even higher if these systems are connected with renewable energy sources (Canals, L., Martinez-Laserna, E., Amante, B., Nieto, 2016).

Moreover, by using less energy during peak demand hours, electrical utilities can reduce the production of energy from non-renewable energy sources (Heymans et al., 2014).

Concerning the social aspects, the deployment of the use of energy storage systems is favoured by its eco-friendly character what makes it easier to be well received by the society. In the same way, new behaviours will appear by regulating the self-consumption of electricity.

Also, it will bring some societal benefits such as the more effective integration of renewables, the reduction in air emissions from generation and improved utilization of grid assets (Eyer & Corey, 2010).

11.2 Fast charging stations

Currently one of the main barriers for the penetration of EVs is the non-existent massive infrastructure of recharging stations. Furthermore, the speed of public charging is often expected to be similar to conventional refuelling (Gnann et al., 2018). In this sense, discarded traction batteries could be also of interest for charging infrastructures.

Even if the majority of recharging nowadays is done at home, several studies have concluded that in areas where drivers have access to 50 kW or 120 kW fast charge stations, the annual EVs miles travelled increased over 25%, even in cases where fast charging was used for only 1% or 5% of total charging events (Ahmed et al., 2017; D. Howell, S. Boyd, B. Cunningham, S. Gillard, 2017).

Currently, according to the European Commission, there is one public recharging point for every five EVs. These add to the number of semi-public (for instance, in commercial car parks) and private recharging points. Nevertheless, it is expected that around 440000 publicly accessible recharging points will be needed by 2020, and some 2 million by 2025 (Niestadt & Bjørnåvold, 2019).

Figure 13 shows the evolution in the number of available charging points in the European Union and Norway. It can be seen that normal power chargers have been deployed at much higher rates than high power ones till the moment.

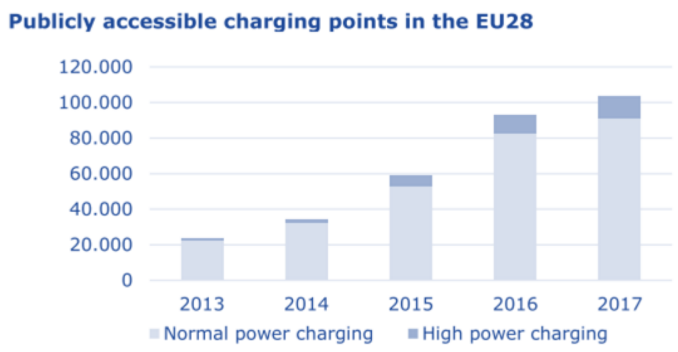

Figure 13. Number of Publicly accessible charging points the European Union and Norway. Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

Tesla is also trying to accelerate the industry's growth through the development of superchargers. Currently they have a platform of 500 stations with 4700 superchargers across 24 countries in Europe. In their charging stations they include "destination charging connectors" which allow charging other vehicle brands. These stations are strategically located in travel routes and they are broadening their charging locations within city centres as well. A map with the location of these stations in Europe is shown in Figure 14.

Until the moment, the average charging time was around 30 minutes but they have already reduced this time with the development of the V3 supercharging technology with 250 kW of peak power (Tesla, 2019).

Figure 14. Tesla's supercharging network in Europe. Source: (Tesla, 2020)

EVs can be either recharged with AC sources or with DC chargers. AC mode is typically associated with domestic chargers and overnights charging and it is limited to 3-6 kW (Ligen, Vrubel, & Girault, 2018). In these cases, the portable charging cable that comes with the EV enables to plug it directly into an available AC outlet and the vehicle's on-board charging equipment converts the power into DC power to charge the batteries. However, it is most common to use charging stations that enable the daily charging in residential and commercial settings (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018).

When it comes to fast charging, the DC fast charging provides power at higher rate than most AC chargers (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018). They convert the power from the grid to DC power required for direct battery charging. Nevertheless, its costs are also higher that the ones of an AC charging station but provides charge in much less time. The mean charging time for a fast charging station is around 30 minutes (Yong & Park, 2017).

Nowadays, most DC chargers provide power at 50 kW but we can also find charges at 100-150 kW power levels, that can serve for the next generation of EVs with will have much bigger batteries (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018).

The charging process can also be based on renewable power supply as the batteries can storage generated power from solar or wind sources offering a CO_2 neutral mobility. The idea is to introduce a buffer energy storage system to take into account the intermittency of the renewable production and to be able to fulfil charging demand at any time (The International Renewable Energy Agency, 2019).

Moreover, energy metering systems could be introduced so that batteries are recharged from the network at low demand times, and that in the long term, recharging points could also allow EVs to feed power from the batteries and back into the network (Niestadt & Bjørnåvold, 2019).

It must be considered that EV charging will represent an important load on the power system with the increase of energy consumption peaks. This could turn into a significant additional cost to the power system, mainly network related investments. In contrast, smart charging could provide a net benefit, by reducing our dependence on fossil fuel power plants and improving the stability of renewable energy sources (Ll Canals Casals & Amante García, 2016; Element Energy, 2019; The International Renewable Energy Agency, 2019)

The estimation of investment and installation costs as well as the annual maintenance costs gathered in various studies for fast charging stations are presented in Table 32. If we pay attention to 50 kWh or 150 kWh stations, it can be clearly seen costs have fallen by half or even more from 2012 to 2020.

Power (kW)	Year	Investment and installation (€)	Annual cost (€/year)
50	2012	90.000	4000
50	2015	35.000	3000
50	2020	36.500	3650
100	2020	46.500	4650
150	2015	120.000	3000
150	2020	59.000	5900
250	2012	125.000	1000

Table 32. Costs assumptions for fast charging stations in various studies. Source: (Gnann et al., 2018)

On the other hand, the main benefits of this solution will rely on the price of the energy and the maintenance fees charged to customers. According to the current tendency in the energy market, it can be considered the energy price increases 25% each year and given the information in previous chart, we can assume the maintenance costs will decrease 5% each year.

As previously mentioned, the average charging time for fast charging stations is 30 minutes, so that means 48 car batteries can be fully recharged daily. However, to pose a more realistic scenario we are going to consider an occupation of 70%.

The expected cost of the energy in kWh for each year are presented in Table 33 as well as the maintenance fees paid by every vehicle. Note that this fee has been computed dividing the total maintenance costs between the number of vehicles that will use the recharging station.

	Benefits	
Year	Energy costs (€/kWh)	Maintenance costs (€/vehicle)
1	0,11	0,30
2	0,14	0,28
3	0,17	0,27
4	0,21	0,26
5	0,27	0,24

Table 33. Expected energy and maintenance costs for recharging point's users. Source: own elaboration

Taking into account the information in Table 10, the cash flows for each year of the investment are shown in Table 34. Costs have been estimated for a 50-kWh charger in 2020 (Gnann et al., 2018) and benefits are obtained for an annual recharge of 12264 vehicles taking into account the energy price and the maintenance costs.

Year	Costs (€)	Benefits (€)	Cash flow (€)	Accumulated cash flow (€)
0	36500,00		-36.500,00	-36.500,00
1	3650,00	60.309,68	56.659,68	20.159,68
2	3650,00	74.292,10	70.642,10	90.801,78
3	3650,00	91.824,88	88.174,88	178.976,66
4	3650,00	113.792,86	110.142,86	289.119,51
5	3650,00	141.302,24	137.652,24	426.771,76

Table 34. Economic analysis of repurposed batteries employed in fast charging stations. Source: own elaboration

According to the calculations made we obtain a pay-back period of 1,64 years and an NVP of 222.237,66 € assuming a 15% discount rate for a 5 year investment. Given that, we could state this could be an economic feasible solution for extending batteries lifetime.

Considering the environmental aspects, EVs powered by the present European electricity mix offers the opportunity of reducing by 10% to 24% the global warming potential compared to conventional diesel or gasoline vehicles (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013). This value can be improved if they are completely powered with energy from renewable sources. That's why it is important to define how electric batteries will be charge and the source of energy used, otherwise, using EVs would be just a 'green washing' (Van Den Hoed, 2005).

From a social point of view, the deployment of fast charging stations could solve one of the main barriers for the widespread penetration of EVs which is the lack of a recharging infrastructure and the long charging times (Gnann et al., 2018) .

11.3 Mobile applications

Batteries can be also reused for mobile means in vehicles with lower power demand and performance requirements.

In the mobile application, both industrial and private or commercial solutions are conceivable. For the industrial sector, a market growth from 1,6 million of vehicles to 2,4 million is expected by 2020.

Due to the high degree of electrification, industrial trucks (for instance forklifts, lift trucks and transport trolleys) constitute a potential medium for discarded traction batteries as well as cleaning machines such as floor sweepers (Richter et al., 2016).

In these cases, the required battery size can widely vary. Whereas small machines partly get along with batteries in a dimension of 0.2 kWh, for example a larger counterbalance fork-lift needs more than 80 kWh batteries (Schlick, Hagemann, Kramer, Garrelfs, & Rassmann, 2012).

One of the main advantages of reusing batteries for this purpose is that a reprocessing of batteries is hardly or not at all necessary (Richter et al., 2016).

Till the moment, lead acid batteries have been used for this purpose, however lithium ion batteries present several comparative advantages as they can be easily charged so they are not out of commission for a long time and it is avoided to have a reserve battery. Also, vehicles carrying lithium-ion batteries maintain a constant speed, even on slopes, that is not possible with lead-acid batteries (Schlick et al., 2012).

The initial investment needed for lithium ion batteries is still higher than for lead acid ones (Schlick et al., 2012). Nevertheless, savings in the production and development could help to impulse its use. In addition, as battery costs are expected to decrease in future years (Element Energy, 2019), the difference between both options will be reduced .

The development of a standard module for these applications could also impulse the penetration of these batteries in the industrial machinery sector (Schlick et al., 2012).

Even if the use of these batteries is still more expensive than common ones, lead acid batteries are less efficient from an environmental point of view and with second life batteries the demand for material production will be reduced (Albright, Edie, & Al-Hallaj, 2012).

The use of discarded lithium ion batteries in an industry could help enhance the image of a company and be part of their social responsibility policies that could lead to an improvement of the company’s reputation and attract customers.

11.4 Decentralised events energy supply

Music festivals have recently turned into a phenomenon, they have grown in both attendance and frequency worldwide (Mair, J. & Laing, 2012).

As these events are rising in popularity, consumers are becoming more demanding. They want to consume ethically, and they expect leisure organisations to take its environmental responsibility seriously (de Brito & Terzieva, 2016). Moreover, Governments, corporate sponsors, local communities and stakeholders are asking for sustainable and responsible events (Musgrave & Pelham, 2011).

Some of the key environmental impacts of festivals include waste, water contamination, air and noise pollution, energy consumption, and impacts on flora and fauna (O’Rourke, Irwin, & Straker, 2011).

When it comes to the total electricity consumption of a festival it can be roughly broken down by thirds, in terms of stage related electricity consumption, trader related activity and site infrastructure. The share of total consumption that each one represents is shown in Figure 15.

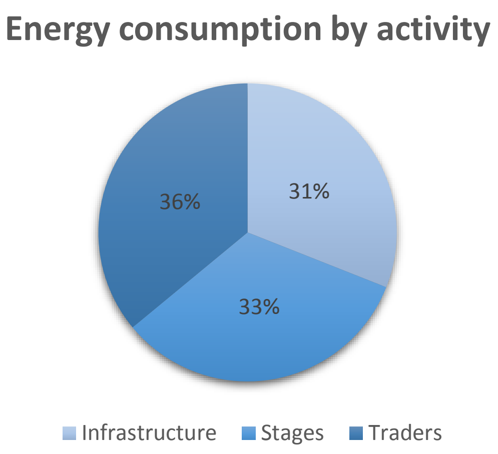

Figure 15. Energy consumption by activity. Source: (Marchini, Fleming, & Maughan, 2013)

Till the moment they have been powered using diesel generators and the elevated energy consumption can represent up to 70% of an event's core carbon footprint (Green Festival Alliance, 2012).

According to a report that analysed various UK summer festivals, the industry produces every year 20 kilotonnes of CO_2e (onsite emissions), 100 kilotonnes CO_2e annually and 23500 tonnes of waste. These data clearly show the actual model of festivals is unsustainable as they consume large amounts of resources and are considerably inefficient in terms of lightning and operations equipment. That's the reason why in recent years, many festivals have accomplished several projects to reduce its environmental impact (Ashdown, 2010).

The most common practices include waste management, recycling or encouraging access by public transport or bicycles (Zifkos, 2015). In order to minimise energy consumption many festivals have started using LED lighting, introduced monitoring of generators and fuel consumption or even diversifying towards renewable sources (Johnson, 2017). Some examples of initiatives carried in several European festivals are described in Table 35.

Festival	Location	Measures to reduce energy consumption
Boom Festival	Portugal	Solar energy has been introduced and now the event is powered by a mix of off-grid photovoltaic panels, diesel generators and a 100kW waste vegetable oil generator.
Øya	Norway	The festival uses grid power, which is 98% renewable-derived (mainly through Norway's hydroelectricity generation).
Cambridge Folk Festival	England	Energy efficient and low emission generators have been introduced and it is also partially run off mains electricity, supplied through a green tariff, which saves 12-15,000 litres of diesel per event and makes a massive saving on the carbon footprint.
Eden Festival	Scotland	The main reggae stage at the festival is powered by a Reaction Sound System which uses audience participation to power small to medium-sized stages with specially designed bike generators. The audience can see how

		much power the pedalled bikes have created through responsive meters that show how much energy is available in the storage system.

Table 35. Examples of energy saving measures in different festivals. Source: (Johnson, 2017)

In this context, repurposed lithium ion batteries from EVs could be used to power all the strands in a festival and substitute diesel generators. A case study where this possible solution is evaluated can be checked in Appendix 2.

The total of traders in the festival proposed to be analysed present a daily energy consumption of 3052,8 kWh that could be totally powered by refurbished batteries.

In order to determine whether this option could be economically feasible, we are going to evaluate the repurposed battery purchase cost, which is estimated on 50$/kWh (J. Neubauer, K. Smith, E. Wood, 2015) and the average cost of a 3000W diesel generator, which is estimated in 270€ according to current selling prices review.

Concerning the energy costs, the electricity price for the batteries performance is 0,07938 €/kWh (Tarifaluzhora, 2020) and the consumption of a typical diesel generator set is 0,53 l/kWh at its rated power (Jakhrani, Rigit, Othman, Samo, & Kamboh, 2012) with a diesel price of 1,318 €/l (DieseloGasolina.com, 2019). The calculations for the total cost of both solutions, given the equipment costs and the energetic expenses for their operation is shown in Table 36.

	Equipment costs	**Energy costs**	**Total costs**
Battery	915.840,00 €	242,33 €	916.082,33 €
Generator	5.400,00 €	2.132,50 €	7.532,50 €

Table 36. Economical comparison of repurposed batteries vs. diesel generators. Source: own elaboration

As expected, there is a considerable difference between both solutions, mainly due to the high price of batteries which makes this solution non-attractive from a financial point of view. When it comes to the operation costs, these are smaller for the batteries system, however the difference does not offset the total costs.

Even though this solution is much more expensive than current generators, it must be taken into account its environmental benefits as it can avoid producing tonnes of greenhouse gases just in one festival.

It must be considered the pollution when transporting the batteries or generators and during operation. The emission factor of a diesel truck is 2,61 kg of CO_2/litter (Oficina Catalana del Canvi Climàtic, 2011) and the average consumption is 30 litters per 100 km. Meanwhile, during operation, 2,67 kg of CO2 are released to the atmosphere per every litter of diesel burned (EPA, 2016).

The estimated emissions of CO_2 for both solutions is presented in Table 37. Note that transportation ones can be considered equal, but batteries can avoid the emission of more than 4 tons of CO_2 for the prototype of festival analysed.

	Transportation (kg CO_2 /100 km)	**Operation (kg of CO_2)**
Battery	78,3	0
Generator	78,3	4320

Table 37.Comparison of CO2 emissions from batteries and generators. Source: own elaboration

Furthermore, from a social point of view, music festivals gather large groups of people together and they can be very powerful forces for inspiration, motivation and awakening change for a better world (Stettler, 2011). They have the opportunity to contribute to the transition of sustainability and influence the environmental practices of their audience beyond the event itself (O'Rourke et al., 2011).

12. Conclusions

As the number of EVs in the roads increase, several initiatives for extending batteries lifetime after being removed from these vehicles are being deployed. In this project, three options for discarded batteries have been assessed.

The direct reuse strategy is presented as the most economically favourable, as the operations that have to be performed in the battery are minimum. In the same way, it is the most optimal from an environmental point of view, as all components can be reused.

On the other hand, the repurpose strategy is a more expensive and arduous solution. Nevertheless, the final product can be perfectly adapted for any application, which makes this option preferable to the previous one in many cases.

These renewed batteries could enhance the deployment of grid-connected energy storage systems and therefore, the reliability, efficiency and cleanliness of the grid. Also, its use for fast recharging stations, or as a power source for mobile and decentralised applications, present several environmental benefits.

In this study, the recycling business hasn't been evaluated as the number of discarded batteries wasn't high enough to make it profitable. However, considering a different scenario, battery recycling is highly necessary as a last step, to recover some valuable materials as lithium or cobalt. In this sense, there are already important recycling companies that have developed improved methods in order to recover a high percentage of the materials with a lower energy consumption.

However, the feasibility of all these processes depends on the amount of batteries available, which will increase in the next years due to the exponential growth in EV sales, and the cost of the technology used, that will probably improve in a close future as many researches are being undertaken in order to develop more efficient technologies that will lead to shorter times and less costs.

The evaluation of the SOH of the battery should be addressed in order to design more competitive procedures and later classify them according to some standard conditions, as well as the automation of time-consuming and risky operations as the dismantling process.

Eventually, the ever-increasing presence of EVs in the market will boost the reutilisation of batteries, and at the same time it will bring economic benefits and the initial cost of the battery can be reduced, encouraging the purchase of EVs. In the end, this will lead to a cleaner transportation system and a more reliable energy system.

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Appendix 1

The location of a battery collection and repurposing for a second life plant

Abstract

The purpose of this paper is to stablish the location of a battery collection and repurposing for a second life plant that will receive used lithium ion batteries from electric vehicles. In order to make a decision, technical, environmental and economic factors will be evaluated.

A weighed decision-making method will be adopted to choose the most accurate location and the suitability of the final result will be discussed.

Keywords electric vehicle · lithium ion battery · recycling· location

Introduction

The need for urgent and more drastic solutions to reduce the effects of climate change is worldwide recognized. In this sense, the widespread deployment of electric vehicles (EVs) is a promising approach for decarbonisation of transport (Vanesa Ruiz et al., 2016). They offer the possibility of replacing fossil fuels used in internal combustion engine vehicles with renewable energy sources, allowing considerable reductions in CO_2 emissions from the automotive sector (Zackrisson et al., 2010).

Sales of electric vehicles are expected to increase rapidly in the next years. According to the International Energy Agency (IEA), the number of EVs will increase from 2 million units in 2016 to 56 million by 2030 (Bernhart et al., 2017).

However, several economic and ecological challenges arise from the production of lithium-ion batteries, which are the most popular type of batteries used in electric vehicles(L. Li, Dababneh, & Zhao, 2018) due to their high energy and power density and long life (Nitta et al., 2015).

Currently most of these batteries are landfilled or disposed in some other way because environmental regulations concerning end-of-life batteries are not fully developed or implemented in many countries (Steward et al., 2019).

As the number of EVs increases, there is need to have well-defined end-of life strategies for the batteries removed from EVs as a way to transform the auto industry to an environmental friendly one (Ramoni & Zhang, 2013). These batteries are one of the key components of the car and they comprise several valuable materials such as cobalt, lithium or copper which can be recovered by recycling at the end of life (Bankole, Gong, & Lei, 2013) so that they could supply a significant fraction of the materials needed for manufacturing new batteries (Steward et al., 2019).

The most common recycling methods are the pyrometallurgical, the hydrometallurgical or a combination of both (Treffer, 2018), and some companies have also developed their own technologies (Sonoc et al., 2015).

The main driver for recycling end-of-life batteries is expected to be the lower cost of recycled materials as well as environmental and social aspects including savings in cost, energy and greenhouse emissions (Steward et al., 2019).

Another option for end of life batteries is to extend their life cycle in a new application as their useful in-vehicle lifespan is approximately 8 years or when 20% of the battery's initial capacity is lost (L. Li et al., 2018). It involves transferring used batteries from an EV application into a second, less demanding one where energy and power density are less critical (Richter et al., 2016; Vanesa Ruiz et al., 2016).

Possible second-life applications differ widely, not only energy storage dimensions, but also in their purpose and field of use. Some aim at a permanent use, others for an emergency or back-up supply (Richter et al., 2016).

These topics are still in their early stage of development (Warner & Warner, 2015). One of the first commercial pilot battery recycling plants was built in Sweden in 2004 with a nominal throughput of 2000 t of batteries per year. Currently, there are industrial plants with an overall capacity of 350.000 t (Treffer, 2018).

These plants could contribute to the transition to a circular economy as the one described in Figure 1. The value chain starts with design and manufacturing. After first life, the battery's health and capacity are checked and if a second life is possible, the battery is refurbished. Finally, as the last step, the battery is recycled (Olsson, Fallahi, Schnurr, Diener, & van Loon, 2018).

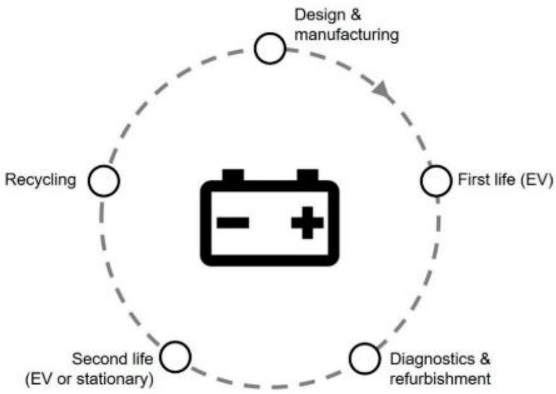

Figure 1. Batteries life cycle. Source: (Olsson et al., 2018)

Hence, the aim of this paper is to define the most optimal location of a battery collection and repurposing for a second life plant that will receive used batteries from EVs and will either repurpose or either recycle them.

Methodology

The collection and repurposing for a second life plant will be placed in Europe. A list of several alternative countries for the exact location of the plant will be proposed in this paper.

Deciding which option is the most suitable is a complicated task because normally there are assessment criteria that are opposed to each other. That is, the most economic feasible solution can be the less viable from a technical point of view.

To avoid this issue, technical, economic and environmental variables will be analysed below for all possible locations and then the relevance of each of them will be defined. Thus, the pros and cons of each solution will be highlighted.

Variable: Electric vehicle sales

The fleet of EV in each European country is a decisive factor for choosing the location of the plant as it will help us to figure out the amount of available batteries that can arrive to the plant in the following years.

Using data taken from the database EV Volumes, which contains statistics about the European EV market, we are going to select a list of countries in order to later assess different influencing factors for each of them.

In Figure 2 we can check the number of EVs sold in 2018 in various European countries and the percentual growth compared to the previous year.

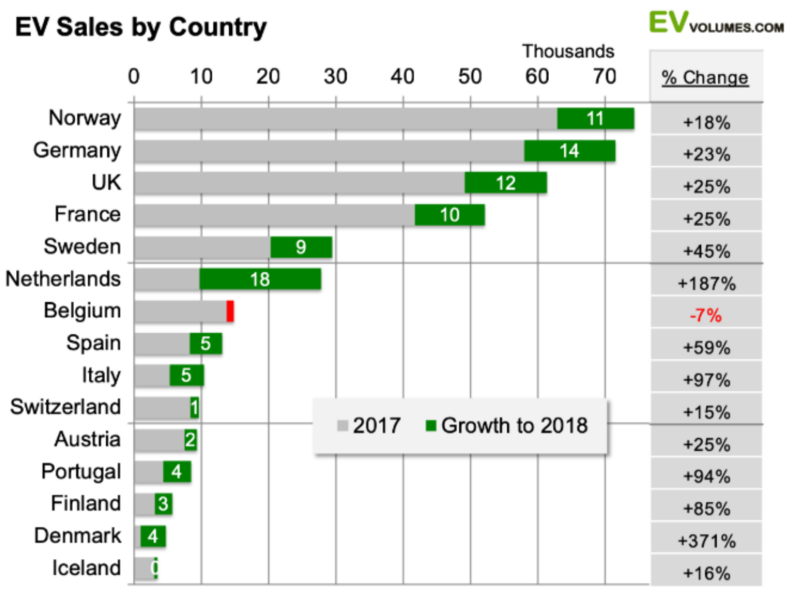

Figure 2. EV sales by country in 2018. Source: EV-Volumes

Considering these data, for this study only the countries with sales over 10.000 units and a positive percentual growth will be contemplated.

Given that, the selected countries and the number of EV sales in 2018 for each of them are shown in Table 1.

Country	EV sales in units (thousands)
Norway	77
Germany	74
UK	62
France	52
Sweden	29
Netherlands	28
Spain	13

Table 38. EV sales in 2018 in the selected countries. Source: EV-Volumes

Variable: Charging infrastructure

One of the main barriers for the penetration of EVs is the non-existent massive infrastructure of recharging stations (Yong & Park, 2017) which is essential to facilitate the development of electromobility (EEA, 2016).

The availability of charging infrastructure in the European Union (EU) has been steadily increasing, similarly to the total stock of EVs (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018).

Figure 3 provides an overview of the status of electromobility in Europe in 2017. The plug-in electric vehicle stock and publicly available charging points of the EU Member State and Norway are shown.

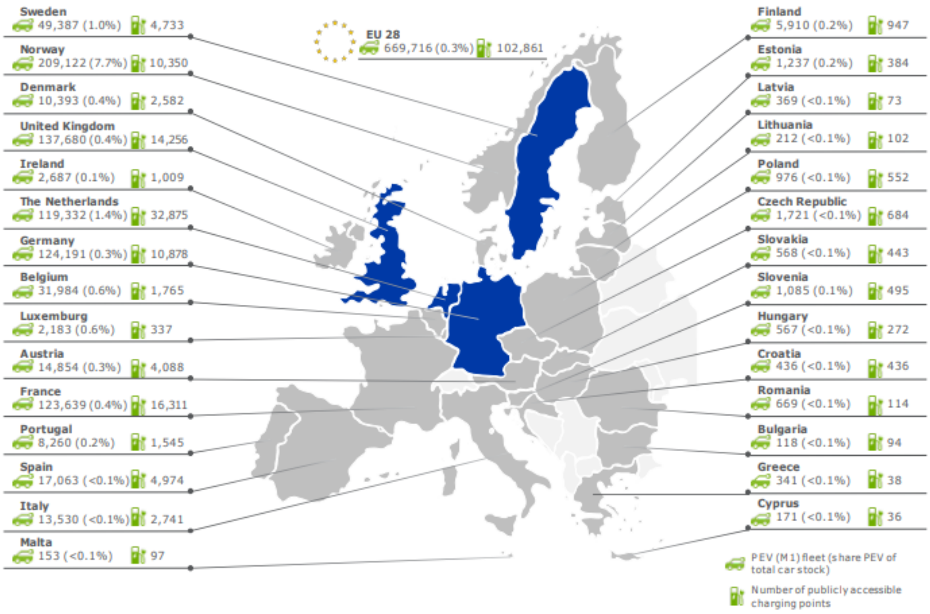

Figure 316. Number of PEVs and publicly accessible charging points in Europe (2017). Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

In view of the selected countries, Table 2 shows the number of publicly accessible charging points in Europe for each alternative.

Country	**Charging points (units)**
Norway	10350
Germany	10878
UK	14256
France	123639
Sweden	4733
Netherlands	32875
Spain	4974

Table 39. Number of charging points in the selected countries. Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

Variable: Recycling infrastructure

The Article 23 of Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators, regulates the manufacture and disposal of batteries in the European Union with the aim of improving the environmental performance of batteries and accumulators.

Batteries are not a particular environmental risk when they are safely used or stored, but if spent batteries are landfilled, incinerated or improperly disposed of at the end of their life, the substances they contain risk entering the environment, affecting its quality and affecting human health (European Commission, 2019a).

The directive requires Member States to ensure that appropriate collection schemes are in place for waste portable batteries and sets a target for the collection rates of 25% in weight of the amount placed on the market by 2012 and 45% by 2016. It also requires Member States to set up collection schemes for waste automotive batteries (European Commission, 2019a).

In 2012, 20 Member States had achieved the 2012 target for collection rates of portable batteries, set at 25% and 14 countries met in 2016 the collection target of 45% (European Commission, 2019a).

The evolution of collection rates for portable batteries in the European Union is shown in Figure 4.

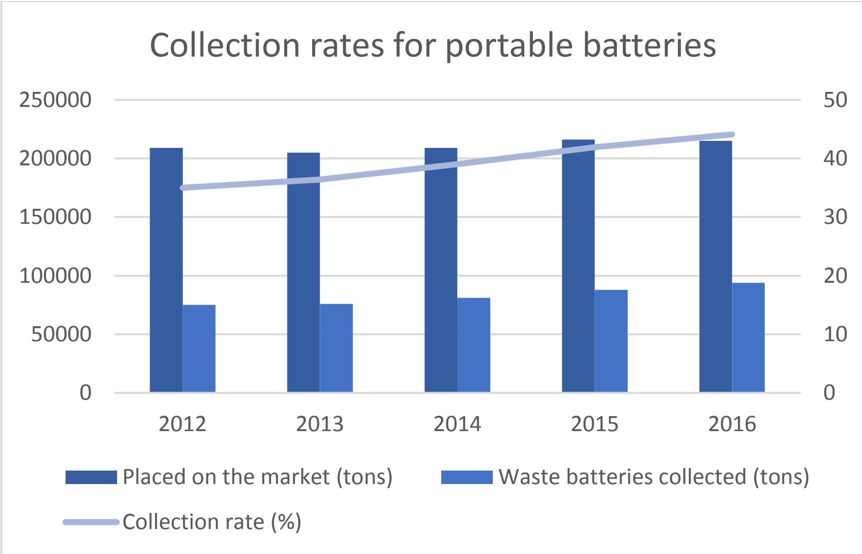

Figure 4. Collection rates for portable batteries in the EU. Source: (European Commission, 2019a)

In Table 3 the collection rates achieved in each of the alternative countries by 2016 are shown.

Country	Collection rate (%)
Norway	51
Germany	46,2
UK	44
France	44,5
Sweden	45,1
Netherlands	49
Spain	38,2

Table 40. Collection rates in the selected countries. Source: (European Commission, 2019a)

Variable: Clean energy

The increased market share of EVs is seen as an opportunity to reduce the dependence on fossil fuels and reduce the emissions of greenhouse gases (Cusenza et al., 2019). However, this can only be achieved if they are powered with renewable energy sources (Nordelöf et al., 2014).

The deployment of the use of energy from renewable sources is one of the main priorities of the European Union, which has established a target of at least 32% renewables energy gross final energy consumption by 2030 under the Directive 2018/2001 (European Commission, 2019b).

Table 4 provides and overview of the share of total production of renewables energies by 2017 in the selected countries.

Country	Clean energy share (%)
Norway	6,6
Germany	36,8
UK	13,2
France	19,6
Sweden	53
Netherlands	13,4
Spain	51,3

Table 41. Clean energy production share in the selected countries. Source: (Eurostat, 2019)

Variable: Government Incentives

The governments active policy support is a major factor for the widespread adoption of EVs. Thereby, countries that promote electric vehicles are providing policy support such as purchase subsidies, public expenditure, tax reduction, tax exemption, free charging and parking permissions (Yong & Park, 2017).

These measures can be implemented at different governance levels, from EU legislation that provides a framework promoting low emission vehicles under several directives, through national measures such as introducing lower taxes for electric vehicles, to local incentives such as free inner-city parking (EEA, 2016).

Table 5 gives an overview of the incentives for electromobility and charging infrastructure provided in the selected countries by 2017. These include bonus payments to encourage the purchase of EVs, reductions in registration and annual circulation taxes or even exceptions for new vehicles, local incentives and investment in charging infrastructure.

Country	Bonus payments and premiums	Tax benefits	Local incentives	Charging infrastructure incentives
Norway	x	x	x	x
Germany	x	x	x	x
UK	x	x	x	x
France	x	x	x	x
Sweden	x	x		
Netherlands		x	x	x
Spain	x	x	x	x

Table 42.Comparison of the selected countries incentives for EVs. Source: (Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., Drier, W., Gartner, 2018)

Variable: Corporation tax

When it comes to the economic variables affecting the location of the plant, the corporation tax is one of the main taxes a business must pay. The current rate for each of the selected countries are shown in Table 6.

Country	Corporation tax (%)
Norway	22
Germany	30
UK	19
France	31
Sweden	21,4

Netherlands	19
Spain	25

Table 43. Corporation tax in the selected countries. Source: (European Union, 2019)

Variable: Workforce average price

The workforce costs are an important part of any business expenses, therefore, its average price (including wages and salary and other additional costs) in each of the selected countries will be evaluated for the final selection of the plant and are shown in Table 7.

Country	Average price (€/h)
Norway	50
Germany	34,6
UK	27,4
France	35,8
Sweden	36,6
Netherlands	35,9
Spain	21,4

Table 44. Workforce average price in the selected countries. Source:(eurostat, 2017)

Decision procedure

Once we have defined a list of possible locations for the plant and the external factors that will be analysed, a weight is assigned to each factor in order to prioritise them, according to the influence they will have on the final choice. These weights are provided in Table 8.

Factor	Weight (%)
Sales	40
Charging infrastructure	30
Recycling rates	15
Clean energy	30
Government incentives	25
Corporation tax	5
Workforce average price	10

Table 45. Weight for each decision factor. Source: own elaboration

Given the values in Tables 1, 2, 3, 4, 5, 6 and 7, the normalized values for each factor of decision are shown in Table 9.

Note that these values have been scaled from 1 to 5 in order to avoid working with very low numbers.

	Alternatives							
	Norway	**Germany**	**UK**	**France**	**Sweden**	**Netherlands**	**Spain**	**Weight (%)**
1. Sales	5,00	4,81	4,06	3,44	2,00	1,94	1,00	40
2. Charging infrastructure	1,19	1,21	1,32	5,00	1,00	1,95	1,01	30
3. Recycling rates	5,00	3,50	2,81	2,97	3,16	4,38	1,00	15

4. Clean energy	1,00	3,60	1,57	2,12	5,00	1,59	4,85	30
5. Government incentives	5,00	5,00	5,00	5,00	1,00	3,00	5,00	25
6. Corporation tax	4,00	1,33	5,00	1,00	4,20	5,00	3,00	5
7. Workforce average price	1,00	3,15	4,16	2,99	2,87	2,97	5,00	10

Table 9. Scaled values for each alternative. Source: own elaboration

Finally, the technical weighed value [Gülfem Isilar and GülÇin Büyüközkan 2007] of each alternative is computed according to the following equation:

$$VTP = \frac{\sum_{j=1}^{n} p_{ij} \cdot g_j}{p_{max} \cdot \sum_{1=1}^{n} g_j}$$

In the previous expression *VTP* is the technical weighed value, p_{ij} is the score of the alternative i for the criterium j, g_j is the weight of the criterium j and p_{max} is the highest score of the chart.

Results and discussion

The technical weighed value for each alternative is provided in Table 10.

Technical weighed value						
Norway	**Germany**	UK	France	Sweden	Netherlands	Spain
0,6395724	**0,7015891**	0,6058941	0,6886410	0,4790974	0,45831007	0,54208721

Table 460. VTP for each alternative

The optimal solution in this case is Germany, as it is the one that satisfies the most the assessment criteria chosen according to the followed method.

From Table 11, we can see there are several countries (Germany, France, Norway and UK) where the installation of this plant could be feasible, as they present similar percentages. Therefore, it is necessary to make a more in deep analysis of the pros and cons of each of them.

Concerning Germany, it is the second top sales country just behind Norway. The recycling infrastructure is also the second biggest from the analysed countries and the share of energy produced from renewable energies is considerably high. These are the key elements that have led us to this result as they are the factors with the highest weight.

However, Germany still covers an important share of 34,1% of its production with coal (Eurostat, 2019). This historical dependence has led to country to implement the Energiewende ("energy transformation") to reduce the use of fossil fuels. Nevertheless, there are still doubts about the immediate costs and conditions of coal replacement (Hake, Fischer, Venghaus, & Weckenbrock, 2015; Renn & Marshall, 2016).

On the other side, France produces three quarters of their total energy using nuclear sources (Eurostat, 2019) and even thought the country has set the goal of reducing this share to a 50% by 2025, there is much scepticism whether it can be achievable (Dalton, 2017).

Meanwhile in the UK the main electricity sources are the natural gas and fossil fuels and in Norway they depend mostly in natural gas and crude oil (Eurostat, 2019).

From an environmental point of view, an important factor for the location of the plant that should also be considered is the closeness to the markets from where retired batteries will be collected. Countries such as Germany or France located in central Europe are the most accurate as transport emissions could be minimized.

From an economic perspective, due to the classification of lithium-ion batteries as hazardous materials, their retrieval will suppose a significant cost (J. Neubauer, K. Smith, E. Wood, 2015). Therefore, reducing them by avoiding longer trips is highly beneficial for the business.

Given the aforementioned issues, Norway and UK are not a feasible solution according to their geographical position.

Moreover, the average rent of industrial land in Germany is 64,56€ per square meter and year, and 57,67€ in France. In Norway and in the United Kingdom the costs are higher, 950 NKr and 73,35 £ which are 93,02€ and 87,30, respectively (considering the current exchange rate of the day 2nd of February of 2020) (Cushman & Wakefield Research, 2011).

Finally, we are going to assess the economic viability of this business model, considering the plant was stablished in Germany. For these calculations we are going to assume an annual input of 1440 batteries and that 60% of them will be repurposed and 35% directly re-used. The costs associated to each option are summarized in Tables 11 and 12, where it can be checked that the direct reuse option is the cheapest strategy as it implies minimum adaptations in the battery.

However, to these costs we have to add the price the plant will pay to the battery owner which will be considered 24$/kWh (21,80 € according to the exchange rate of the day 11th of March of 2020). Given that, the total cost of repurposing and reusing the battery are 44,61€ and 36,63€, respectively.

If we consider batteries will be sold at a price of 50$/kWh(J. Neubauer, K. Smith, E. Wood, 2015) (45,42€ given the exchange rate of the day 11th of March of 2020) the margin profit will be of 0,45€/kWh and 8,36 €/kWh for the repurposing and reusing strategies respectively.

Concept	**Annual expenses (€)**
Transportation	86.276,05 €
Labour	158.664,96 €
Energy costs	841,65 €
Rent	13.653,36 €
Other direct costs (2% labour)	3.173,30 €
Total direct costs	262.609,32 €
Insurance	7.878,28 €
G&A	42.017,49 €
Warranty	10.504,37 €
Total	323.009,46 €
Cost per battery	641,11 €
Cost per kWh	**15,26 €**

Table 11. Cost per kWh for the direct reuse strategy. Source: own elaboration

Concept	Annual expenses (€)
Transportation	147.901,80 €
Labour	313.823,04 €
Energy costs	1.189,99 €
Materials	195.196,20 €
Rent	18.854,64 €
Other direct costs (2% labour)	6.276,46 €
Total direct costs	683.242,13 €
Insurance	20.497,26 €
G&A	109.318,74 €
Warranty	27.329,69 €
Total	840.387,82 €
Cost per battery	973,01 €
Cost per kWh	**23,17 €**

Table 12. Cost per kWh for the repurposing strategy. Source: own elaboration

From the values obtained it can be stated the margin profit is really tight. Nevertheless, the earnings are expected to increase in the following years, as the number of available batteries to recover will be higher due to the growth of sales experimented in the last years.

Conclusions

Overall, this paper analyses some influencing factors when choosing the location of a battery collection and repurposing for a second life plant that will repurpose and recycle lithium ion batteries used in EVs. Attending to the number of EV sales, the availability of charging infrastructure, the share of energy produced by renewable sources, the state and local incentives for the deployment of electromobility and economic factors such as the corporation tax rate and the workforce average price, a decision making method is applied to choose the most favourable option.

The country that obtained the highest mark was Germany, but the value obtained does not differ very much from the one computed for other countries as France, Norway or the United Kingdom.

However, additional factors were evaluated to confirm whether the results obtained are appropriate. On the one hand, in Germany and France, the energy production mix is still highly dependent on coal and nuclear sources, even though they are trying to boost the penetration of renewable energies. On the other hand, both countries are strategically placed in Europe, as they could receive batteries from many countries all around and reduce transportation costs and pollutant emissions and also, the average rental price in these countries is lower than in Norway or UK.

Ultimately, none of the possible locations studied completely meet the requirements proposed but Germany and France are presented as the most favourable ones. Nevertheless, as the value obtained is relatively close to one, we can confirm the solution is promising, despite the fact that it is difficult to forecast the amount of EVs batteries arriving to the plant for the upcoming years.

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Appendix 2
Case Study: Decentralized events energy supply

Abstract
Sustainability in music festivals have become an important research focus in the recent years due to the increase number of these events celebrated annually and the considerable environmental impact they produce.

The elevated energy consumption can represent up to 70% of an event's core carbon footprint (Green Festival Alliance, 2012) because till the moment, they have been powered using diesel generators. However, practices such as the introduction of clean energy sources could contribute to make festivals more environmentally friendly. Given that, this case study analyses the feasibility of powering all the traders in a festival using second life batteries from electric vehicles.

Introduction
Within the last decade music festivals have risen in popularity and they have turned into a big business worldwide (Mair, J. & Laing, 2012; Zifkos, 2015).

These events may only last a few hours or days, but the social and environmental impacts associated with them can extend well beyond the event itself as they have the power to influence the environmental practices of their audience while in attendance and even beyond (O'Rourke et al., 2011).

At the same time, as the world of events is growing, consumers are becoming more demanding. They want to consume ethically, and they expect leisure organisations to take its environmental responsibility seriously (de Brito & Terzieva, 2016). Moreover, Governments, corporate sponsors, local communities and stakeholders are asking for sustainable and responsible events (Musgrave & Pelham, 2011).

Some of the main environmental impacts of these festivals include waste, energy consumption, water contamination, air and noise pollution, and impacts on flora and fauna (O'Rourke et al., 2011).

The typical power use can be broken down into three categories: stages, traders and site infrastructure (Fleming, Marchini, & Maughan, 2014). Stages use audio, video and lighting and these areas are the most energy-intensive, particularly at larger events. Traders include both food and non-food traders providing goods or services, and they use electricity for lightning, cash machines, freezers and fridges among other services. The average energy consumption for each area is illustrated in Figure 1.

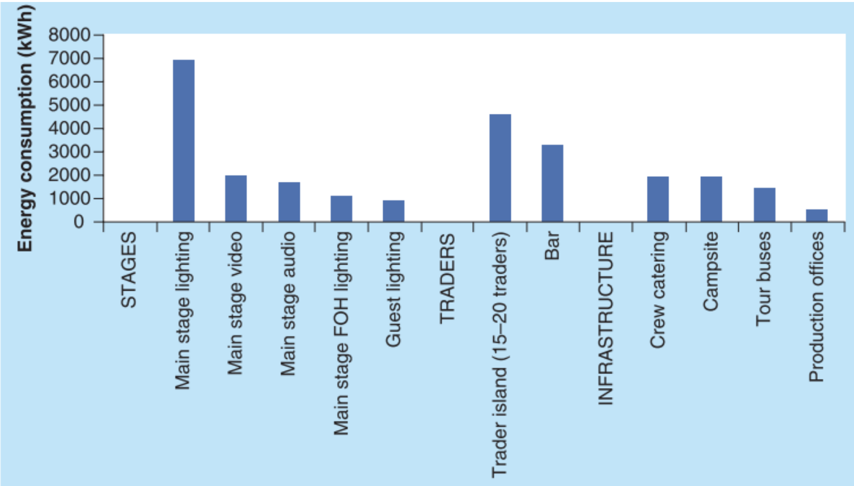

Figure 1. Typical energy consumption by activity. Source:(Fleming et al., 2014)

Currently, almost all music festivals are supplied by diesel fuel generators. In 2011, the UK alone used over 12 million litres of diesel fuel for outdoor music festivals (Green Festival Alliance, 2012). Moreover, energy security is a key issue at these events and for this reason generators are commonly oversized running most of the time at low loads (Fleming et al., 2014; Green Festival Alliance, 2012).

These facts highlight how unsustainable the use of diesel is, as it pollutes the atmosphere, contributing to climate change and a variety of health concerns like asthma and lung disease (Esparza, 2019).

The introduction of more energy-efficient equipment, more renewable energy systems and electrical storage will help to mitigate these issues (Fleming et al., 2014).

In the recent years, the research on this topic has increased and several studies concerning the sustainability of events have been published (de Brito & Terzieva, 2016). They are focus on aspects such as sustainability impacts and models (Raj & Musgrave, 2009), the need for new business models(Musgrave & Pelham, 2011) and barriers an opportunities (Ponsford, 2011).

Some festivals have already adopted environmentally sustainable practices, including waste management, recycling or encouraging access by public transport or bicycles (Zifkos, 2015). In order to minimise energy consumption many festivals have started using LED lighting, introduced monitoring of generators and fuel consumption or even diversifying towards renewable sources (Johnson, 2017).

The main driver for adopting these measures are competitive advantage, image enhancement, supply chain, corporate social responsibility or consumer demand (Mair, J. & Laing, 2012) .

This case study analyses the opportunity of replacing generators by second life batteries used in electric vehicles to power all the traders in a festival, reducing the emissions of polluting gases to the atmosphere and improving the overall energy efficiency of the event.

Methodology

In this case study we will consider the use of repurposed batteries from electric vehicles to power the traders in a music festival.

First, the energy requirements will be evaluated. In Table 1 the typical elements that are found in a trader, their nominal power, hours of daily usage and total daily consumption are presented.

Device	Power (W)	Hours/day	Consumption (Wh/day)
Refrigerator	1200	24	28800
Lightning	300	20	6000
Blender	850	4	3400
Coffee maker	600	7	4200
Total	2950		42400

Table 47. Trader energy consumption. Source: own elaboration

We are going to consider the festival has a duration of 3 days, so the batteries have to be sized to fulfil the energy demand of this period. Given a daily consumption of 42400 Wh, the total demand for the full festival is 127,2 kWh

Taking a depth discharge for the batteries of 80% each trader will need a battery of 152,64 kWh.

The Renault Zoe battery has a capacity of 52 kWh (*Renault Zoe R90 (2018-2019) price and specifications - EV Database*, 2020), so that means around 3 full batteries will be necessary to power one strand.

It can be considered that the typical number of traders in a big festival is between 15 and 20 (Marchini et al., 2013) so the total consumption for the whole festival will be 3052,8 kWh.

Examining at the economic aspects, repurposed lithium ion batteries will be sold at a price of 50$/kWh(J. Neubauer, K. Smith, E. Wood, 2015) and the electricity price for the batteries operation is 0,07938 €/kWh (Tarifaluzhora, 2020).

Finally, it must also be considered the pollution when transporting the batteries or generators. The emission factor of a diesel truck is 2,61 kg of CO_2 /litter (Oficina Catalana del Canvi Climàtic, 2011) and the average consumption is 30 litters per 100 km.

Results and discussion

The economical comparison of using second life batteries versus diesel generators is shown in Table 2. The cost of batteries has been computed for a price of 46,06 €/kWh (given the exchange rate of the day 24th of February of 2019) and the generator price has been taken from pricing review, considering an average price of 270€ for a 3kW of nominal capacity generator and a total of 20 generators.

Meanwhile, for the energetic expenses, the consumption of a typical diesel generator set is 0,53 l/kWh at its rated power (Jakhrani et al., 2012) and the price of diesel is 1,318 €/l (DieseloGasolina.com, 2019).

	Equipment costs	Energy costs	Total costs
Battery	915.840,00 €	242,33 €	152.882,33 €
Generator	5.400,00 €	2.132,50 €	7.532,50 €

Table 48. Economical comparison of repurposed batteries vs. diesel generators. Source: own elaboration

It can be appreciated the high difference between both solutions, as the actual battery price is still too high to make this proposition financially viable. However, it can also be checked that the energy costs are smaller compared to the cost of combustible needed for the generator.

As presumed, when it comes to the environmental impact of both solutions, using refurbished batteries is the most optimal choice. The transportation and operation CO_2 emissions for each system are given in Table 3. Note that transportation emissions have been considered equal for both solutions, as it only depends on the type of truck used. However, for the operation emissions, it can be checked the use of batteries could avoid the emission of 4,32 tonnes of CO_2 for the model of festival described in this case study.

The generator emissions have been computed taking into consideration that 2,67 kg of CO_2 are released to the atmosphere per every litter of diesel burned (EPA, 2016) and a consumption of the generator of 0,53 l/kWh.

	Transportation (kg CO_2 /100 km)	**Operation (kg of CO_2)**
Battery	78,3	0
Generator	78,3	4320

Table 49. Comparison of CO_2 emissions from batteries and generators. Source: own elaboration

Conclusions

The use of second life batteries for partial powering music festivals can help decreasing one of the key environmental impacts of these events which is the energy consumption.

Until the moment, festivals have been powered with diesel generators as it is the most economic option. From the results got in this case study, it can be seen that using second-life batteries is a much more expensive solution. However, taking into consideration that battery prices are expected to fall down next years and so will happen to the energy price, the difference between both systems is expected to be reduced.

Anyhow, from an environmental point of view, the usage of generators is highly unsustainable due to the elevated amount of greenhouse gases they produce when burning the combustible. Meanwhile, batteries produce no on-site emissions and if they are coupled with photovoltaic panels, the energy consumed can be totally clean.

Another comparative advantage of using batteries is that they are more silent that generators and less dangerous as a fuel reserve is not needed.

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