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Master of Science in Management Engineering

Closing the loop of Lithium-ions Batteries:

An investigation over the Critical Success Factors in the automotive sector

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A mamma e papà, che giorno dopo giorno,

mi sostengono in tutto ciò che faccio,

ad Alessandra, che da anni ormai,

condivide con me tappe importanti della nostra vita,

e a tutte le persone che mi sono state vicine

e che hanno reso questo traguardo possibile.

Abstract

Purpose: The purpose of this thesis is to define how to implement a successful Closed Loop Supply Chain for automotive lithium-ions batteries focusing on lithium recycling since, so far, this material is not recovered by spent batteries. Recently, the problem of future remarkable flows of spent automotive Li-batteries is attracting attention of researchers due to the expected exponential diffusion of Electric Vehicles all over the world and on the growing issues related to virgin lithium accessibility. In order to define a framework of proposed actions for the lithium-ions battery system, I used the lead-acid battery system as reference since it is a perfect example of implementation of loop closing solution.

Design/Methodology/Approach: The research was conducted in two phases. Firstly, I performed the literature analysis in order to identify key factors that influence the development of a Closed Loop Supply Chain solution. Then, the case-based research approach was employed to perform empirical examination of lithium-ions battery and lead-acid battery systems based on the factors identified in the first stage. In particular, seven manufacturers, three collectors and seven recyclers were engaged from both batteries systems. After the collection and encoding of data, I examined separately each system. Then, I performed a comparative analysis in order to come up with relevant enablers and bottlenecks.

Main Findings: The comparative analysis demonstrates that the two systems present both similarities and differences. Indeed, following the purpose of closing the loop, legislations, companies' interactions among players of the battery system and network infrastructure are seen by both the systems as enabling conditions. In particular, legislation is seen by all the actors a fundamental driver. The main differences are among lithium-ion battery and lead-acid battery manufacturers in terms of technological aspects (product design and recycling technologies), financial aspects, and quality of recycled materials. The former ones consider all these factors as bottlenecks for Closed Loop Supply Chain; instead, the latter ones as enablers. The Li-batteries recyclers give also attention to volume of end-of-life batteries, an important factor that allows recyclers to achieve economies of scale. These bottlenecks are very important as indications for actions needed for the development of the Closed Loop

Supply Chain for Li-batteries. In particular, the battery technology must be standardized, the recyclers have to invest in new recycling technologies, precise targets for collection and recycling must be set, etc.

Research Limitations and Implications: The analysis is limited by the number of companies considered and the geographical scope of consideration. Therefore, given the variety of stakeholders involved in the battery system there is large space for further research. Moreover, as the lithium-ions battery system is still evolving, the framework which I proposed should be reviewed within few years.

Practical Implications: Battery manufacturers and recyclers need to collaborate in order to solve the problems related to the complexity of preforming recycling activities. The design of the Li-battery could facilitate recycling activities by reducing the presence of a high variety of materials with the replacement of few materials in larger quantity. In addition, the recycling implications must be considered from the design stage of the product. Moreover, to solve the problem of volume mixing contamination, a label, which allows to distinguish the different battery technologies, needs to be defined. Finally, policy makers need to define new regulations to improve the recovery of wasted products, to grant incentives to recyclers for making new investments in more reliable and sustainable recycling technologies, and finally to sanction illegal flows of spent batteries.

Keywords: Closed Loop Supply Chain; Recycling; Critical Success Factors; Automotive Battery System; Lithium-ions Battery; Lead-acid Battery.

Abstract (In Italiano)

Scopo: Lo scopo di questa tesi è quello di definire l'implementazione di una filiera a ciclo chiuso (le cosiddette Closed Loop Supply Chain) di successo per le batterie al litio impiegate nelle auto elettriche. In particolare, il focus è incentrato sulla possibilità di riciclare il litio contenuto in queste batterie, dato che ad ora questo materiale non viene recuperato. In questi anni, il problema di come verranno gestiti i volumi futuri di batterie esauste al litio sta attirando l'attenzione dei ricercatori. Ciò è dovuto sia per l'esponenziale diffusione dell'auto elettrica sia per le crescenti preoccupazioni legate all'approvvigionamento del litio. Perciò, per definire delle azioni che potrebbero risolvere le criticità legate alla batteria al litio, ho analizzato il sistema industriale delle batterie al piombo come riferimento in quanto esempio perfetto di implementazione di una filiera a ciclo chiuso.

Design/Metodologia/Approccio: Lo studio è stato condotto in due fasi. Inizialmente ho analizzato la letteratura al fine di individuare i principali fattori chiave che influenzano lo sviluppo di una chiusura della filiera. Poi, sulla base dei fattori definiti precedentemente, ho effettuato un'analisi empirica utilizzando l'approccio di ricerca basato su casi studio per entrambe le due tipologie di batterie (litio e piombo). In particolare, nell'analisi sono stati coinvolti: sette produttori, tre consorzi (raccolta e/o trattamento) e sette riciclatori. Dopo la raccolta e la codifica dei dati, ho esaminato separatamente i due sistemi. Quindi, per ottenere dei risultati ho eseguito un'analisi comparativa tra le due tipologie di batterie.

Risultati Principali: L'analisi comparativa dimostra che i due sistemi presentano sia somiglianze che differenze. Infatti, seguendo lo scopo di chiusura della filiera, le normative, i rapporti di collaborazione tra gli attori appartenenti alla medesima supply chain e l'infrastruttura di raccolta sono considerati da entrambi i sistemi come condizioni abilitanti. In particolare, le leggi e le regole (sia a livello Europeo sia Italiano) sono definite da tutti gli attori considerati come un driver fondamentale. Le principali differenze sono tra i produttori di batterie agli ioni di litio e batterie piombo-acido in termini di aspetti tecnologici (design del prodotto e tecnologie di riciclaggio), aspetti finanziari e qualità dei materiali riciclati. I produttori di batterie al litio considerano i fattori appena menzionati come criticità per la chiusura della supply chain; invece, i produttori di batterie al piombo considerano i medesimi come fattori di successo. I riciclatori di batterie al litio danno molta importanza ai volumi di batterie esauste, in quanto questo fattore permette a chi svolge attività di riciclo di beneficiare di economie di scale. Le criticità evidenziate sono molto importanti in quanto permettono di evidenziare le azioni necessarie per l'implementazione di una supply chain chiusa per le batterie al litio. In particolare, la tecnologia e il design delle batterie devono essere standardizzati, i riciclatori devono investire in nuove tecnologie di riciclaggio, nuovi obiettivi per la raccolta e il riciclaggio devono essere fissati, ecc.

Limitazioni dello studio e Implicazioni: l'analisi è limitata dal numero di aziende considerate e dall'ambito geografico di considerazione. Pertanto, data la varietà di parti interessate coinvolte nel sistema delle batterie, c'è ampio spazio per ulteriori ricerche. Inoltre, poiché la batteria al litio è in continua evoluzione, i suggerimenti proposti potrebbero richiedere future modifiche.

Implicazioni pratiche: i produttori di batterie e i riciclatori devono collaborare così da poter risolvere i problemi legati alla complessità sia della batteria sia delle attività di riciclaggio. Per facilitare le attività di riciclo la batteria deve essere composta da pochi materiali e in quantità maggiori e inoltre, le implicazioni del riciclaggio devono essere considerate dalla fase di progettazione del prodotto. In aggiunta, per risolvere il problema della contaminazione dei flussi di batterie esauste, è necessario che il produttore definisca un'etichetta che consenta di distinguere i diversi tipi di batterie. Infine, la Comunità Europea e i diversi Stati devono definire nuove norme per migliorare il recupero dei prodotti esausti, incentivare i riciclatori a effettuare nuovi investimenti in tecnologie di riciclaggio più affidabili e sostenibili e sanzionare chi svolge attività di riciclo illegali.

Parole chiave: Closed Loop Supply Chain; Riciclo; Fattori critici di successo; Batterie per automobili; Batteria agli ioni di litio; Batteria al piombo.

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Abbreviations

BEV	Battery Electric Vehicle
CDCNPA	Centro Di Coordinamento Nazionale Pile Accumulatori
CLSC	Closed Loop Supply Chain
CNR	Consiglio Nazionale delle Ricerche
CRM	Critical Raw Materials
EC	European Commission
EOL	End Of Life
EPR	Extended Producer Responsibility
EU	European Union
EUROBAT	Association of European Automotive and Industrial Battery Manufacturers
EV	Electric Vehicle
FSC	Forward Supply Chain
LAB	Lead-Acid Battery
LIB	Lithium-Ion Battery
LME	London Metal Exchange
Ni-Cd	Nickel - Cadmium
RL	Reverse Logistics
RSC	Reverse Supply Chain
SC	Supply Chain

Executive Summary

Introduction

Green technologies, also known as clean technologies (e.g. electric vehicles, light-emitting-diode lighting, photovoltaic power systems), are playing a significant role in changing the course of economic growth towards sustainability and they will enable present and future generations to live in clean and healthy environment (Zeng et al., 2014; Eggert, 2017). In particular, great efforts are pushed toward decarbonisation of transport with the introduction of Electric Vehicles into the market. Based on targets set by the European Commission in the “White Paper” (2011), being transport one of the major sources of CO_2 emissions (transport sector accounts for 25% of all CO_2 emission within the EU), electrification is become essential for meeting the EU goals of energy security and decarbonisation.

Therefore, EVs are increasing significantly in the market. Several forecasts establish that by 2040 the electric car sales worldwide will be more than 40 million (Bloomberg Energy Finance, 2017; Ernst & Young analysis, 2016). In particular, one of the most important component common to all electric car typologies is the electric battery.

I decided to focus my attention on batteries since they are at the very heart of the shift towards a decarbonized society, encompassing several industrial sectors, from all modes of transport to energy storage and grid stability. This technology is essential to our modern lifestyle for its ability to provide instant power supply. In the market there are different types of battery technologies available for vehicle electrification needs: nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and lithium-ion (LI). All these batteries answer to different demands in terms of capabilities, applications, performances and all of them are an important part of the solution to the climate change issue and the energy dependence. Nevertheless LIBs are the most adapted and used since the high value of energy density, voltage of cells and lifespan. The increasing trends in use of electric vehicles (we have also to consider a huge increase in electric bicycles and motorbikes) means that a massive growth in the production of electric battery is needed. Thus, to fulfill the production requirements, a huge amount of materials is needed as well.

Cobalt, lithium, nickel, manganese and copper are the most important non-ferrous metals that compose a lithium-ion battery both in terms of value and quantity. Among them, in the last years, growing attention is dedicated to lithium. In particular, concerns about lithium availability and accessibility arose.

Lithium is light, electrochemically active and it has a low thermal expansion coefficient (Elbensperger et al., 2005). Moreover, lithium is the solid metal with the highest electrochemical potential and it has a high gravimetric and volumetric energy and power density. For these reasons, it is expected that lithium-based battery chemistries will dominate the automotive battery market in the near-term and probably in the long-term future, which makes lithium indispensable in the scale-up of electric vehicles (Wadia et al., 2011). The 41% of lithium is used in the production of batteries.

Lithium is a material difficult to extract and geographically concentrated in few countries of the world (Argentina, Chile, China, Australia). This causes problems with the stability and security of the Li-supply. In fact, in a ipotetical scenario, lithium shortages could threaten the EV market supply since the most directly available resources are currently geographically concentrated. Moreover, another problem is that the scale adaptation of current production facilities appears not reactive enough to follow in real-time a highly probable steep growth in lithium demand and thus new investments are required. Therefore, following the reasoning done, lithium is affected by a problem of accessibility.

A solution to this problem is the implementation of LIB recycling activities. In the last years, a lot of experts took into consideration this recovery option (Midema and Moll, 2013; Beheshti and Aune, 2016; Rahman, 2017) since governmemts employed huge efforts on it (e.g. introduction of the Extended Producer Responsibility (Battery Directive, 2006); Circular Economy Package, 2015). The recycling activities would allow to create an additional source of lithium supply (a local one, by the exploitation of urban mines (Hagelüken, 2014; Swain, 2017)) so to increase the security of the supply that is fundamental for Europe. Indeed, Europe is highly dependent on imports of metals and primary resources from European deposits are not available in sufficient amounts for the majority of metals. Moreover, recycling would allow to manage in a sustainable way materials reducing the volume of waste batteries and solving the problem of managing toxic substances embedded in batteries, which if dispode in the environment would create health problems. Finally, it allows to reduce the environmental impacts of mining activities.

Currently, Li-battery recycling processes still focus on the recovery of cobalt and nickel but not lithium. The reason is the higher raw material costs compared to the less expensive lithium (Ziemann et al., 2012; Dunn et al., 2012). If for cobalt, nickel and copper there are not uncertain scenarios since there is a successful recycling process, for lithium the situation is more complex. In fact, an efficient recycling technology able to recover all the scarce and valuable materials for the battery is missing.

Therefore, following the CLSC perspective, defined as the integration of foreward and reverse supply chain (Govindan et al., 2014), the aim of the thesis is to provide a proactive solution to solve the problem of future remarkable flows of EOL LIBs associated with the expected exponential diffusion of EVs. In particular, I decided to investigate which are the critical success factors for the proper implementation of a CLSC solution toward recycling (focus on lithium recycling) for the EOL automotive lithium-ions batteries. To this end the following research question is set forth:

RQ: Which are the critical success factors for the implementation of a CLSC model for automotive lithium-ions batteries?

In order to come up with a solid analysis, I studied the system of automotive LAB as the reference model. The decision is driven by the fact that LAB is the most recycled product worldwide. In fact, it represents a very good example of implementation of CLSC with 99% of material recovery through recycling.

Before performing my analysis, I analyzed the perspectives taken by authors in literature on CLSC in general and then in particular for the automotive sector. In the last twenty years, CLSC became a fully recognized subfield of supply chain management (Guide and van Wassenhove, 2009). In fact, based on economic, legal, social and environmental factors, closed-loop supply chain issues have attracted attention among practitioners and academia. When we are talking about CLSC we refer to the integration of forward supply chain (FSC) and reverse supply chain (RSC) (Govindan et al., 2014; Guide and van Wassenhove, 2003).

The forward supply chain, the linear model of consumption, is the classical form of the supply chain and it is a combination of processes with the aim to fulfill customers' requests. It includes a wide set of entities like suppliers, manufacturers, transporters, warehouses, retailers and customers themselves (Chopra and Meindl, 2010).

Instead, the reverse supply chain is a set of activities that starts from end users where EOL products are collected and managed according to different decisions undertaken by different actors who are involved in the reverse flow. The RSC process can be organized sequentially by five key steps: product acquisition, reverse logistics, testing and sorting and disposition, refurbishing and finally remarketing. Among authors, someone deal with specific topics like the product acquisition activities, the RL process or one of the refurbishing options and others are more oriented to a comprehensive view of all the system. Then, I analyzed in literature how CLSC in the automotive battery industry is discussed and I studied the key publications that deal with RL, RSC, CLSC and different recovery processes. The result is that authors are more focused on recovery options instead of RL, RSC or CLSC. In particular, among the recovery options, the majority is focus on battery recycling an activity able to provide both economic and environmental benefits.

In order to analyze in a comprehensive way the automotive battery industry (focus on LABs and LIBs) in a CLSC perspective, a framework is needed.

The literature offers different set of factors that influence the development of a closed loop system. The different frameworks are characterized by different number and types of factors and different focuses of analysis due to the variety of perspectives taken (CLSC, RL, RSC, recycling activity). Each framework was developed to answer to a particular scope such as CLSC for PV panels (Besiou and Van Wassenhove, 2016), RL in the electronic industry of China (Lau and Wang, 2009), how to perform effective and efficient recycling (Hagelüken, 2014).

Therefore, I decided to select the most representatives in terms of considerations and findings and among them those dealing with technological products in order to have similarities with automotive batteries (Photovoltaic panels (Guide and Van Wassenhove, 2016); EOL computers (Rahman and Subramanian, (2012); electronic industry (Lau and Wang, 2009)).

Since the scope of each individual publication is still limited by the perspective taken and the list of factors considered, I decided to study the different perspectives taken by the different scholars in order to define a comprehensive list of factors useful to describe the battery systems. The papers written by Besiou and Van Wassenhove (2016) and Lapko et al. (forthcoming) are those from which I take the most important insights since they provide a framework for the proper implementation of a CLSC focusing on recycling as recovery option.

Therefore, my list of factors was defined. The aim of this list of factors is the possibility to provide a comprehensive view of CLSC to apply for the battery industry. All these factors will be used as reference dimensions in the following analysis in order to define the critical success factors in terms of barriers and enables both for the lead-acid battery system and the lithium-ion battery system.

Below there is reported the list of factors of my framework with a short description for each of them:

- ✓ *F1_TECHNOLOGICAL ASPECTS:* it refers to aspects related to the battery product design (physical and chemical composition, ease of dismantling) and to the availability of technologies to perform a proper recycling activity.
- ✓ *F2_VOLUME:* this factor refers to the availability of EOL products (as the input of the RSC) and the availability of recycled materials (as the output of the RSC and therefore, the new input of a new SC in the CLSC perspective). In fact, thanks to the recycling processes, it is possible to recover materials that could be reused for the production of new products.
- ✓ *F3_LEGISLATION:* it refers to directives, policies and regulations set by authorities for different actors along the supply chain (e.g. mandatory certifications of recycling activities; incentives and recycling targets; take back legislations). They are considered the starting point that force companies that produce batteries to think in a close loop perspective. When a company decides to produce and sell a battery in the market, it has to be aware that it will have to care about the managing of the same battery at the EOL according to the EPR (Batteries Directive, 2006/66/EC).
- ✓ *F4_ORGANIZATIONAL SET UP*: the factor is related to the network structure and the set of companies involved along the SC with their different modes of operations and different level of responsibility (e.g. battery manufacturers → Extended Producer Responsibility).
- ✓ *F5_INFRASTRUCTURE:* (also in terms of geographic proximity) is defined as the means through which is possible to perform a success CLSC. This factor refers to the availability of enough means, facilities, capacity and right technologies in order to allow the performing of collection, sorting, mechanical and metallurgical processing. All together these elements ensure that EOL products are available for recycling.
- ✓ *F6_COMPANIES INTERACTIONS:* defines the different interactions that companies create in pursuit the close loop perspective as collaboration, cooperation for the purpose of sharing information, knowledge and infrastructures and competition. Indeed, Pursuing CLSC activities means put together different supply chain actors.
- ✓ *F7_FINANCIAL ASPECTS*: refers to the overall financial flows related to the activities that contribute to the close loop perspective. It considers the cost/benefits analysis and the presence of economic incentives (e.g. investments in infrastructures, in technologies, in personnel and in products design activities;

costs of collection; costs of the recycling process; value of second-hand materials).

- ✓ *F8_QUALITY*: the factor characterizes the level of purity of recycled materials from EOL batteries. To operate the batteries must be characterized by high quality of the materials that make up them. In particular, the recovered materials in order to be reused for the production of new batteries need to have a level of purity above of a certain threshold, otherwise it can not be use in the production process of the same product but maybe it can be reused in other applications where the requirements are lower.

Research Methodology

In the literature analyzed, the majority of authors use a qualitative research approach based on case study (Besiou and Van Wassenhove, 2015; Lau and Wang, 2009, Lapko et al., forthcoming; Knemeyer et al., 2002). As Yin (2009) said, the preference for qualitative research approaches is driven by the opportunity to examine and gain in-depth understanding of complex phenomenon. These approaches are preferred when "how" and "why" questions are being posed, when the investigator has little control over events and when the focus is on contemporary phenomenon within some real-life context.

Therefore, given the uncertainty that characterized the LIBs system, as done by Besiou and Van Wassenhove (2015), I decided to use a case-based research approach in order to obtain direct information from the main stakeholders involved in the battery industry (battery manufacturers, collectors and recyclers). This decision is driven by the features of the CLSC that is a complex system where multiple actors are involved in pursuing their own objectives.

In order to achieve the aim of my work, I consider two automotive battery systems: the lithium-ion battery system and the lead-acid battery system. The companies that are important to consider for both the lead-acid battery and the lithium-ions battery systems are battery manufacturers, logistics providers and recyclers. Furthermore, in my analysis, I considered also some associations which have the aim to control and coordinate the set of actors involved in the battery system. This allows me to gather additional information from actors that are not directly involved into the operations.

Since until now, in Europe a CLSC for LIB is not in place, I decided to focus my attention on the European boundaries, in particular focusing my attention on Italy. All the companies selected are located within the EU, as geographical scope plays an important role due to different industrial infrastructure, different availability of materials, different technological competences and different environmental legislations.

Then, firstly, I collected data through interviews and analysis of secondary data and secondly, I coded indications for factors in all the data collected (both primary and secondary) for both the battery systems and I tried to define implications of each factor. Finally, I analyzed each factor according to different perspectives. The same process is used to analyzed the two battery systems. The generic process followed consists of three steps:

- ✓ At the beginning, I analyzed each factor within each company in order to investigate how each factor affects the way of working of each company following a closed loop perspective; I defined for each factor pro and cons.
- ✓ Then, I analyzed each factor within each supply chain position in order to examine the behaviors of the different players in pursuing the CLSC. Maybe a factor that is considered a bottleneck for manufacturers, by the recyclers is seen as an enabler.
- ✓ Finally, I analyzed each factor throughout time This allows me to define possible milestones over the years that affect the implementation of the closed loop supply chain for the specific battery system. For example, since the LAB is a mature technology compare to the LIB, from an analysis throughout time it is possible to discover important events that affected the development of the LAB CLSC. Maybe, these events could be replicated for the success of the LIB CLSC.

Analysis

Lead-acid batteries are the world's most recycled consumer product. The success of this system is proven by a study (The Availability of Automotive Lead-based Batteries for Recycling in the EU) performed by EUROBAT between 2010 and 2012. The research establishes that the collection and recycling rate of automotive lead-acid batteries over the period 2010/2012 was equal to 99%. Over the total amount of automotive batteries available for collection (1,110,730 tons), the total amount of automotive battery collected was 1,093,645 tons in the two years under investigation. Therefore, according to the research conducted by EUROBAT, more than 99% of all lead-acid batteries are recycled compared to the 68%[1] of aluminum soft drink and beer cans, the 72 %[2] of paper and the 70%[3] of glass bottles.

The 80% of a typical lead-acid battery is composed by materials that are recycled from oldest batteries (EUROBAT, 2015). In fact, the battery's production, distribution and recovery cycle follows a virtually "closed-loop". The EOL lead-acid batteries, instead of being dumped in landfills, are collected by authorized actors and they are sent to recycling centers where the recovery activities are performed under strict environmental regulations. From 2006, such activities are regulated by the EU Battery Directive (2006/66/CE) that promotes a high level of collection and recycling of waste batteries and a better environmental performance of all operators involved in the life cycle of batteries.

Based on the battery manufacturer perspective, the most relevant factors are *Legislation* (F3) and *Organizational Set Up* (F4), which represent the drivers that force them to perform additional activities for the recovery of their EOL products. They have to fulfil these obligations otherwise, if they fail to comply with them, they have to face costly sanctions. The other two important factors are *Financial Aspects* (F7) and *Technological Aspects* (F1). The former (F7), following the aim of closing the loop, is affected in two opposite ways:

- ✓ Cash outflow: the manufacturer has to pay a fee to the collectors in order to finance the collection system (- €);
- ✓ Saving of money: the manufacturer can save money by buying recycled lead at a lower price than the virgin one.

Therefore, even though battery manufacturers see the fee payment negatively, the same, by funding the system that allows the CLSC, can gain cost advantages.

The latter factor (F1), the technological one, is important because it is considered a facilitator of closing the loop. The manufacturers argued that thanks the simple and standard battery design the performing of recycling activities is not a problem and therefore, they can fulfil easily their product responsibility.

[1] European Aluminium Association 2013

[2] Confederation of European Paper Industries 2013

[3] European Container Glass Federation 2014

Based on collectors, since their role in the CLSC is the fulfilment of the battery manufacturer responsibility making EOL LABs available for recovery activities, the most relevant factors are those related to the functioning of network system and to the definition of different relationships among companies. Indeed*, Organizational Set Up* (F4) and *Infrastructure* (F5) are fundamental for the proper implementation of the CLSC. Through the implementation of collective schemes and the right definition of the infrastructure, which is able to guarantee a high collection rate, collectors can meet the battery manufacturers' responsibilities and they can make large amount of EOL LABs available for recyclers. Moreover, the *Companies Interactions* factor (F6) is fundamental for collectors. In fact, different issues can be considered:

- ✓ Sharing of information with battery manufacturers: this allows to efficiently organize the collecting activity because it boosts the visibility of collectors on possible future flows of EOL batteries (e.g. number of lead-acid batteries sold into the market in a particular time window, forecast of EOL LABs, number of returned batteries);
- ✓ Sharing of the infrastructure among battery manufacturers: this allows collectors to reach economic advantages in terms of economies of scale. In fact, for example, the collector can use the same truck to collect lead-acid batteries from different battery manufacturers.

Finally, they consider as important factor the *Legislation* (F3) because it obliges producers to take responsibility for their batteries; therefore, regulations allow collectors to carry out sustainable economic activities.

Based on recyclers, the most important factors are those related to the Financial Aspects (F1) and Technological Aspects (F7). In fact, the positive financial result obtained from the recycling activities is a fundamental aspect that ensures the feasibility of materials recovery in pursuing the CLSC for LABs. The main reason that allows recyclers to consider the LAB a valuable product is the high price of lead in the London Metal Exchange (LME) market. Indeed, the actual price of lead allows recyclers to perform profitable activities. The other important aspect is the technological one. In fact, the recycling process is simple and standard and it reflects the simplicity of the battery design. This allows recyclers to perform recycling activities without problems.

Moreover, recyclers give relevance to *Volume* (F2) and *Quality* (F8), as important factors that amplify the success of the recovery activities. In fact, Volume (F2) is fundamental because considering the remarkable quantity of LABs collected, recyclers can reach the maximum plant capacity and therefore they can exploit economies of scale. In addition, since the output of the recycling process is secondary lead with high purity level, recyclers become the first supplier of lead material in the market against mining companies. For this reason, the high importance given to *Quality* factor (F8).

Finally, they recognize the importance of *Companies Interactions* (F6) and *Legislation* (F3). The former has relevance because through the collaboration of recyclers and battery manufacturers, new and better recycling technologies can be born.

The latter, instead, is seen in a similar way to the collectors' perspective: it allows having a large number of EOL LABs to be recycled.

If I shift the analysis to the second battery system, among the existing BEV technologies, the lithium-ions battery (LIB) is considered the best technology for sustainable transport due to its high energy and power per unit battery, which allowing it to be the lighter and smaller than other rechargeable batteries. The lithium-ion battery is characterized by a high variety of chemical elements and compounds: H, Li, C, O, F, Al, Si, P, Ti, Mn, Fe, Co, Ni, Cu, Sn (Herrmann et al., 2012). It is a quite complex product because it consists of several LIB cells controlled by a battery management unit (BMU) to prevent deep discharge or overcharging and to monitor the cells' state of health. In these years, one of the biggest concern linked with the EV boom is that this exponential diffusion could leave 11 million tons of EOL LIBs in need of recycling between now and 2030 (IEA, 2017).

Based on the battery and EV/battery manufacturer perspective, the most relevant factors of LIBs CLSC are *Technological Aspects* (F1), *Legislation* (F3) and *Organizational Set Up* (F4). F1 is seen as a criticality because recyclers with the available recycling technologies are not able to recover all the materials embedded in the lithium-ion battery. The main reasons are: the high variety of materials and chemicals in the battery, the presence of different designs and the value of materials. F3 and F4, instead, represent the drivers that force them to perform additional activities for the recovery of their EOL batteries. They have to fulfil these obligations otherwise, if they fail to comply with them, they have to face costly sanctions. Moreover, for battery manufacturers, *Quality* (F8) (if things do not change) is seen as a future bottleneck condition due to the high variety of materials and chemicals in batteries (problem of contamination). Instead, for EV/battery manufacturers, *Companies Interactions* (F6) acquires huge importance as enabler of collaborations with other actors in order to solve criticalities both at the production and at the recycling stage.

Based on collectors, according to their role in the CLSC, the most relevant factors are those related to the functioning of network system and to the definition of different relationships among companies. Indeed, *Organizational Set Up* (F4), *Infrastructure*

(F5) and *Companies Interactions* (F6) are fundamental for the proper implementation of the CLSC. Collectors can decide to share information with battery manufacturers in order to properly manage the collection activities to reach high efficiency and high service level. Moreover, collectors can avoid the mixing of LIBs with LABs with the sharing of information with battery recyclers. This allow reducing the risk of fires and explosions at the recycling facility. Finally, they consider as important factor the *Legislation* (F3) because it obliges producers to take responsibility for their batteries; therefore, regulations allow collectors to carry out sustainable economic activities.

Based on recyclers, the most important factors are those related to the *Technological Aspects* (F1), the *Volume* (F2) and the *Financial Aspects* (F7). F1, with the actual recycling technologies, is considered a bottleneck. There is not a technology able to recover all the materials in the battery achieving satisfactory results in terms of efficiency, economic feasibility and environmental pollution. The main reason is the presence of a high variety of different lithium-ions battery technologies characterized by different materials and chemicals. Therefore, recyclers in order to perform economic feasible activities (F7), according to the value of each material, prioritize the recovery of materials that cover the production costs. Moreover, the product complexity affects also the *Quality* (F8) of recovered materials. In fact, with the actual technologies, the level of purity of recovered materials (in particular for lithium) is not acceptable for the production of new batteries. The other element of criticality is F2 because the flows of EOL LIBs are not big enough to allow reaching economies of scale. Nowadays, activities are managed in batches and it means losing of money and operational efficiency. However, it is a momentary issue. With the exponential diffusion of EVs, recyclers are confident that in a few years, the volume of EOL LIBs will increase. Finally, they recognize the importance of *Companies Interactions* (F6) and *Legislation* (F3). The former (F6) has relevance because recyclers and battery manufacturers can collaborate in the definition of battery designs easy to recycle and recycling technologies able to recover all the materials embedded in the battery. Thus, the collaboration can boost the sharing of technical knowledge and information so that both parties can benefit from it. The latter (F3) is considered as an enabling condition because ensure the availability of high volumes of LIB (Battery Directive and EPR). However, regulations are also a factor of uncertainty because, in the future, possible laws could make outdated actions and investments (new technologies and new plant capacity, *Infrastructure* (F5)) made so far.

From the comparative analysis of the two battery systems, the result is that for Technological Aspects (F1), Volume (F2), Financial Aspects (F7) and *Quality* (F8) there is a quite opposite situation. In fact, if these factors are seen mainly as enablers from LAB actors, for LIB actors there are see mainly as bottlenecks. Instead, *Legislation* (F3), *Organizational Set Up* (F4), *Infrastructure* (F5) and *Companies Interactions (*F6) are characterized by similar considerations for both the systems.

The main difference between the two systems is that the LAB is seen as a source of value by the actors involved in the CLSC of such product. In fact, the LAB, with its simple and standard configuration (F1), with the availability of a standard technology able to recycle lead-acid batteries in an easily way (F1) and with the presence of remarkable flow of EOL products in the market (F2), is able to guarantee a source of revenues (F7) for the players involved in this particular system. The LIB, instead, is considered a source of costs characterized by different issues. In fact, all the enablers conditions described for the LAB, in the case of LIB are bottlenecks. Indeed, so far in the market there are different varieties of LIB technology (F1) which feed different recycling technologies (F1). Not only the technological considerations are problematic; the volume (F2) is a critical factor for the implementation of a CLSC for LIBs. The small volume of EOL LIBs is not able to allow LIB actors to gain money (F7). Moreover, the high volatility of the lithium market price is a further factor of uncertainty of the system.

Finally, also F8 is fundamental for the determination of the CLSC. In fact, the high purity of recycled lead and its lower price compared to the virgin one push battery manufacturers to buy secondary lead. Instead, so far recovered lithium and manganese (albeit in very small quantity) are not seen valuable recycled materials due to the contamination of other materials.

The other factors, instead, are quite similar. In both the systems, there are players that are obliged to fulfill the requirements of take-back EOL batteries (EPR, F4) according to the set of regulations (Battery Directive and further integrations) defined at the European and at the National levels (F3). Moreover, the different actors involved in the two systems use the same infrastructure (F5) for what concern the collection activities. However, this has a double valence: a positive one, if we consider that using the same infrastructure, actors involved in the system can perform collection activities efficiently and a negative one, if we consider that the sharing of infrastructure can create problems of mixing batteries flow and thus creating problems at the recycling plant stage.

Finally, the actors in both systems agree on seeing the relevance of F6. In fact, the possibility to define relationships among the different players of the SC allows to establish collaborative environments and to favors the exchange of technical knowledge and information.

In conclusion, the bottlenecks that come out by the performing of such comparative analysis are very important because they serve as indications for actions needed to develop the CLSC for LIBs. Moreover, important insights are suggested by the enablers of LABs which provide important evidence of conditions that support the development of a CLSC for batteries. Therefore, based on the comparative analysis performed, which are the lessons learned that the LIB system could implement in order to define a successful CLSC for the EOL automotive LIBs? Below, for each factor, all the proposed actions for the success of CLSC for automotive LIB are summarized.

Factors	**LIB Future Actions:**
F1 - Technological Aspects	Product design standardization: minimum number of components, standardization of materials and formats and avoiding the utilization of toxic metals; Design for separation/disassembly: utilization of nuts and bolts instead of welds; Design of recycling: manufacturers have to shift from a material centric approach to a product centric approach. Introduction of new recycling technologies able to recover all the materials embedded in the LIB (ongoing projects).
F2 - Volume	It is a matter of time. A collection system is already present. In order to have remarkable flows of EOL LIBs, operators have to wait some years until the products reach their end of life
F3 - Legislation	New regulations in terms of: New targets for collection and recycling (minimum recycling rate) Incentive mechanisms in order to stimulate recyclers to make investments in new technologies Measures against illegal flows of EOL batteries
F4 - Organizational Set Up	(no operations are defined)
F5 - Infrastructure	In order to solve the problem of volume mixing contamination, manufacturers can define a label in order to distinguish the LIBs from the other battery technologies
F6 - Companies Interactions	Batteries manufacturers and recyclers need to collaborate in the definition of product specifications in order to bring benefits to both of them.
F7 - Financial Aspects	It is mainly a matter of market dynamics. The driver that conditions the material recovery is the market price.
F8 - Quality	In order to avoid recovered material contamination problems, the battery must be composed by the minimum number of different materials.

Conclusions

This thesis addresses the problem of performing a successful CLSC for end-of-life automotive LIBs in which the lithium recycling is performed. By the execution of an analysis over two battery systems, the lead-acid batteries systems and the lithium-ions one, I extend the knowledge on the implementation of a CLSC focusing on recycling as a product recovery option. In particular, LAB system serves as a reference point to further develop a roadmap for the LIB system. In order to understand the actual situation and examine the systems following the key features of the CLSC, I developed a framework of eight factors to conduct my analysis. I collected information through interviews and secondary data and I considered European and Italian players involved in the most representatives supply chain positions (manufacturers, collectors and recyclers).

The analysis demonstrates that the two systems have both similarities and differences. Indeed, by making a comparative analysis the result is that, so far, the most critical factors for a proper implementation of a CLSC for LIBs are:

- ✓ the technological aspects (both in terms of battery design and recycling technology),
- ✓ the low availability of EOL LIBs managed by collectors and recyclers,
- ✓ the actual regulations that not provide specific requirements for LIB technology,
- ✓ and the volatility of material market prices that creates uncertainty in the market.

Based on the examination of both LAB and LIB system, I suggested a framework of actions needed to enable the CLSC of LIBs with the performing of efficient lithium recycling activities. Based on this framework, below I provide implications for business actors and policy-makers.

For example, recyclers and manufacturers need to collaborate in order to solve the problems related to the technological aspects. The LIB must be composed by lower different materials and it must be designed according to the principles of design for disassembly/recyclability. In order to solve the problem of volume mixing contamination, LIB manufacturers need to define a label which allows to distinguish LIBs from other battery technologies.

Moreover, my findings could be helpful to policy makers in their efforts to improve the recovery of wasted products. In fact, for the proper definition of a successful CLSC for LIBs further regulations must be set. In particular, new regulations are needed in order to set precise responsibilities among players involved in the system, to incentives recyclers to make new investments in more reliable and sustainable recycling technologies and to sanction illegal flows of EOL LIBs.

However, a number of uncertainties still exist. First of all, it is difficult to estimate exactly the trend of EVs growth and the consequent waste flow of LIBs. Moreover, new trajectories of LIBs battery technology and recycling technologies deployment could bear thanks to recent research. Indeed, particular attention is given to the research conducted by Cobat and CNR, which are trying to define a reliable and eco-sustainable technology for the treatment of EOL LIBs.

Finally, this study presents some limitations and it offers several prospects for further research. First of all, the findings obtained are the result of an analysis that engaged with several companies from three SC positions (manufacturers, collectors and recyclers). Further research will benefit from examination of greater number and type of stakeholders. Indeed, given the multiple stakeholders involved in the battery system who either facilitate the development of CLSC activities or create barriers, and the complexity of their operations and decision making processes, there is large space for further research. Moreover, the actors considered are mainly Italian and European. Therefore, a global picture is missing. Lastly, as the LIB system is still developing, in the next years there might be technological progress both in terms of battery and recycling technology, more restrictive regulations and different market dynamics (EVs sold in the market, lithium market price), etc. Therefore, the proposed framework should be revised accordingly.

Chapter 1
Introduction

Sustainability is one of the core themes of the twenty-first century and presents a truly global challenge. Green technologies are playing a significant role in changing the course of economic growth towards sustainability and they will enable present and future generations to live in clean and healthy environment (Zeng et al., 2014; Eggert, 2017). These technologies (e.g. electric vehicles, light-emitting-diode lighting, photovoltaic power systems), which are also known as clean technologies, refer to the development and extension of products, processes and practices that improve or replace the existing technologies facilitating society to meet their own needs with a consistent reduction of human impacts on the planet.

In particular, based on the challenge of sustainable development, the use of electricity is become a great opportunity for decarbonisation of transport (European Commission, 2017a). The EC, in the "White Paper" (2011), stated the goal to reduce the GHG emissions by around 20% until 2030 compared to emissions in 2008, and by 60% until 2050 compared to 1990 (European Commission, 2011). Transport sector accounts for 25% of all CO_2 emission within the EU. Therefore, being transport one of the major sources of CO_2 emissions, electrification is become essential for meeting the EU goals of energy security and decarbonisation.

In this scenario, Electric Vehicles[4] (EV) are increasing significantly in the market. Bloomberg says electric vehicle sales worldwide have reached just under half a million in 2015, an increase of 60 percent over the previous year (Bloomberg Energy Finance, 2017). Although EVs account for only one per cent of the total vehicle fleet at present, electric car sales worldwide will be more than 40 million by 2040, or around 35 percent of all sales of light commercial vehicles (Figure 1).

[4] *Electric Vehicle*: is is a vehicle powered by an electric motor instead of a gasoline engine. The electric motor gets energy from a controller, which regulates the amount of power—based on the driver's use of an accelerator pedal. The EV uses energy stored in its rechargeable batteries, which are recharged by common household electricity.

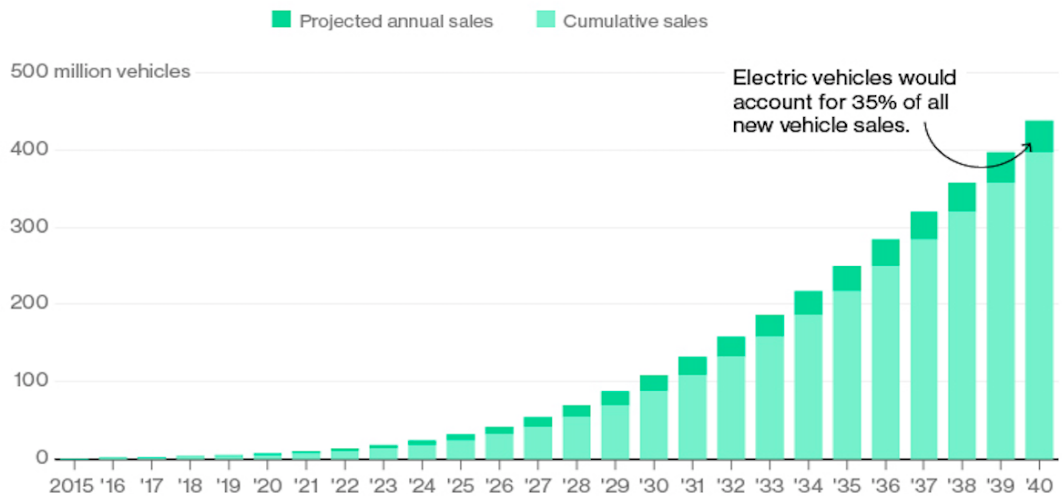


Figure 1: Forecast EV sales, Bloomberg New Energy Finance (BNEF).

To confirm this, an analysis performed by Ernst & Young (EY analysis, 2016) shows the results that came out comparing different studies on EV adoption in the long run. The result is a long-term EV penetration ranging from 10% to over 35% until 2040 taking into consideration factors like different technical advancements, different policies support in R&D or infrastructure and different emission standards.

Different types of EV exist: Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV) and Extended Range Electric Vehicles (E-REV) (Energy & Strategy Group, 2017). Several key components are fundamental for the pursuing of the electrification issue and one of them is the EV battery.

Therefore, I decided to focus my attention on batteries since they are at the very heart of the shift towards a decarbonized society, encompassing several industrial sectors, from all modes of transport to energy storage and grid stability. Indeed, batteries are essential to our modern lifestyle since they are able to make our lives convenient because of instant power supplied. In the market there are different types of battery technologies available for vehicle electrification needs: nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and lithium-ion (LI). All these batteries answer to different demands in terms of capabilities, applications, performances and all of them are an important part of the solution to the climate change issue and the energy dependence. Nevertheless LIBs are the most adapted and used since the high value of energy density, voltage of cells and lifespan. For these reasons, in the last years the actors in the automotive battery industry are pushing a lot of efforts especially on this technology. In fact, some important players have made huge investments in LIB production plants. For example, Tesla Motors, the Californian company founded by Elon Musk, promised to produce 1 million of lithium-ion electric vehicles batteries by the end of the next decade (Tesla Gigafactory[5]) (Forbes, 2017). In general, the LIB electric vehicle is driving investments all over the world for a total amount of hundreds of billions of dollars (e.g. the German Daimler, the Korean LG Chem) (Bloomberg Energy Finance, 2017).

Therefore, the increasing trends in use of electric vehicles (we have also to consider a huge increase in electric bicycles and motorbikes) means that a massive growth in the production of electric battery is needed. Thus, to fulfill the production requirements, a huge amount of materials is needed as well.

Cobalt, lithium, nickel, manganese and copper are the most important non-ferrous metals that compose a lithium-ion battery both in terms of value and quantity. Among them, in the last years, growing attention is dedicated to lithium. In particular, concerns about lithium availability and accessibility arose. Indeed, lithium is difficult to extract and geographically concentrated in few countries of the world. This causes problems with the stability and security of the Li-supply.

A solution to this problem is the implementation of LIB recycling activities. In the last years, a lot of experts took into consideration this recovery option (Midema and Moll, 2013; Beheshti and Aune, 2016; Rahman, 2017) since governments employed huge efforts on it (e.g. introduction of the Extended Producer Responsibility (Battery Directive, 2006); Circular Economy Package, 2015). The recycling activities would allow to create an additional source of lithium supply, i.e a local source, by the exploitation of urban mines (Hagelüken, 2014; Swain, 2017), so to increase the security of the supply that is fundamental for Europe. Indeed, Europe is highly dependent on imports of metals and primary resources from European deposits are not available in sufficient amounts for the majority of metals. Moreover, recycling would allow to manage in a sustainable way materials reducing the volume of waste batteries and solving the problem of managing toxic substances embedded in batteries, which if dispode in the environment would create health problems. Finally, it allows to reduce the environmental impacts of mining activities.

5 *Tesla Gigafactory:* is the biggest operational lithium-battery factory in the world (under construction). It is powered by solar energy and it is defined the first milestone toward the "electric revolution".

Currently, Li-battery recycling processes still focus on the recovery of cobalt and nickel but not lithium. The reason is the higher raw material costs compared to the less expensive lithium (Ziemann et al., 2012; Dunn et al., 2012). If for cobalt, nickel and copper there are not uncertain scenarios since there is a successful recycling process, for lithium the situation is more complex. In fact, an efficient recycling technology able to recover all the scarce and valuable materials for the battery is missing. The global rate of lithium recycling is only < 1% (Swain, 2017). Instead, at the European level the lithium recycling rate is equal to zero (European Commission, 2017c). For this reason, different researchers aim to understand if there will be enough lithium on the planet to feed the global market (Grosjean et al., 2011; Kushnir and Sanden, 2012; Kesler et al., 2012; Vikström et al., 2013; Ziemann and Weil, 2012). In the last years, experts (Gruber et al., 2011; Zeng and Li, 2014; Hanisch et al., 2015; Hoyer, 2015) said that a future shortage of lithium is predicted within the next 100 years for scenarios without the application of recycling processes able to regain the 90% of the used lithium.

Following the Closed Loop Supply Chain perspective, defined as the integration of foreward and reverse supply chain (Guide and Van Wassenhove, 2003; Govindan et al., 2014), the aim of my thesis is to explore the feasibility of a proactive solution to solve the problem of future remarkable flows of EOL LIBs associated with the expected exponential diffusion of EVs. Therefore, I decided to investigate the critical success factors for the proper implementation of a CLSC solution toward recycling (focus on lithium recycling) for the EOL automotive lithium-ions batteries. To this end the following research question is set forth:

RQ: Which are the critical success factors for the implementation of a CLSC model for automotive lithium-ions batteries?

Moreover, in order to come up with a solid analysis, I studied the system of automotive LAB as the reference model. The decsion is driven by the fact that LAB is the most recycled product worldwide. In fact, it represents a very good example of implementation of CLSC with 99% of material recovery through recycling.

The work is divided into eight chapters, as follows. In Chapter 2 a literature background about lithium and importance of recycling is provided. Moreover, CLSC in general and in the automotive sector are discussed considering different scholar's perspectives. Lastly, I critically discuss the frameworks reported in literature that deal with critical factors for CLSC implementation, from which I selected the of factors adopted for the present study. Chapter 3 is devoted to the methodological approach and therefore, the research approach, the empirical setting, the data collection and analysis are described. Chapter 4 and Chapter 5, report the analysis of the two systems of batteries, LAB and LIB respectively. In Chapter 6, a comparative analysis is performed to come up with the major findings of the study, i.e. enablers and bottlenecks. In Chapter 7, a framework for the development of a CLSC for LIB is finally proposed. Chapter 8 is used to draw the main conclusions along with limitations and suggestions for future research.

Chapter 2
Literature Background

In this section, there is reported an overview of issues about lithium (utilization, availability, criticalities) and the main benefits of performing recycling activities are presented. Then, I provide an analysis based on literature about CLSC in general and focused on the automotive sector (lead-acid and lithium-ions battery). Finally, in order to develop a comprehensive framework useful for my analysis, firstly I provide an overview of the most relevant frameworks analyzed about CLSC and its subsystems (RSC, RL, recovery options) and secondly I describe my list of factors.

2.1 Lithium overview: utilization, availability and criticalities

Lithium is a chemical element and it has the symbol **Li** and atomic number **3** in the periodic table of elements.

It is light, electrochemically active and it has a low thermal expansion coefficient (Elbensperger et al., 2005). Commercially, lithium is used to produce various chemicals, most of which are indispendable to modern industry. Moreover, lithium is the solid metal with the highest electrochemical potential and it has a high gravimetric and volumetric energy and power density. For these reasons, it is expected that lithium-based battery chemistries will dominate the automotive battery market in the near-term and probably in the long-term future, which makes lithium indispensable in the scale-up of electric vehicles (Wadia et al., 2011). The 46% of lithium is used in the production of batteries: 12% for EVs, 1% for electric bicycles, 16% for mobile phones, 12% for laptops and tablets and 5% for power banks and energy storage systems. Moreover, it is involved in the production of glasses, ceramics, lubricating greases and others (Figure 2).

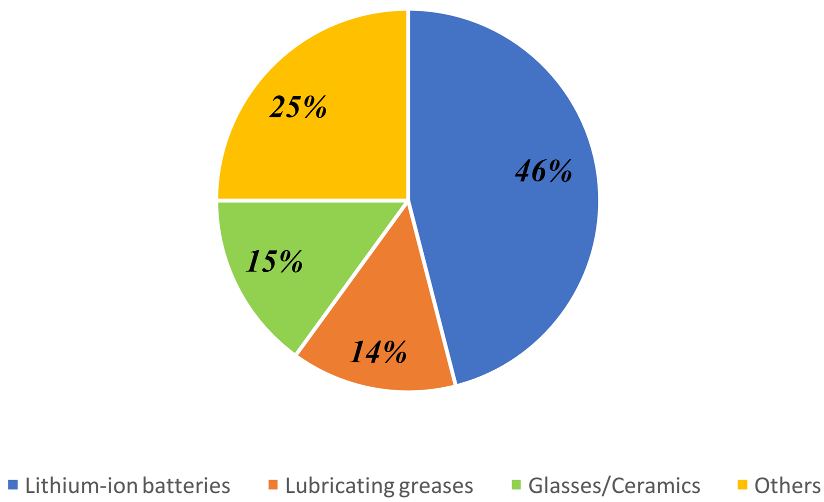


Figure 2: Lithium consumption by application (Hao et al., 2017)

Goldman Sachs (2016), the biggest and most profitable business bank of the world, defines lithium as the "new oil". It claims that, in the following years, based on the increasing diffusion of EVs, there will be an exponential growth of lithium production that compared to the actual production, it will double. Some investors are defining lithium as a new "megatrend" to exploit but others are more cautious.

The lithium market is a true market, albeit dominated by some nations (Argentina, Chile, China, Australia) and few companies in the industry (Figure 3). According to several independent experts the lithium amounts are still abundant and it is difficult to imagine "shortage" or lack of this metal for a long period of time (Yaksic and Tilton, 2009; Gruber and Medina, 2010). They support that there may be presumably stages in which the supply will not be sufficient to meet demand with a certain delay between mining investments and increased supply in a trend where the growth of electric vehicles will certainly be highly sustained. Instead, other experts are less confident about lithium availability and they define it as critical (Kesler et al, 2012; Ziemann and Weil, 2012).

In the last years, experts (Zeng and Li, 2014; Hanisch et al., 2015; Hoyer, 2015) say that a future shortage of lithium is predicted within the next decades if companies do not perform recycling activities able to regain the used lithium.

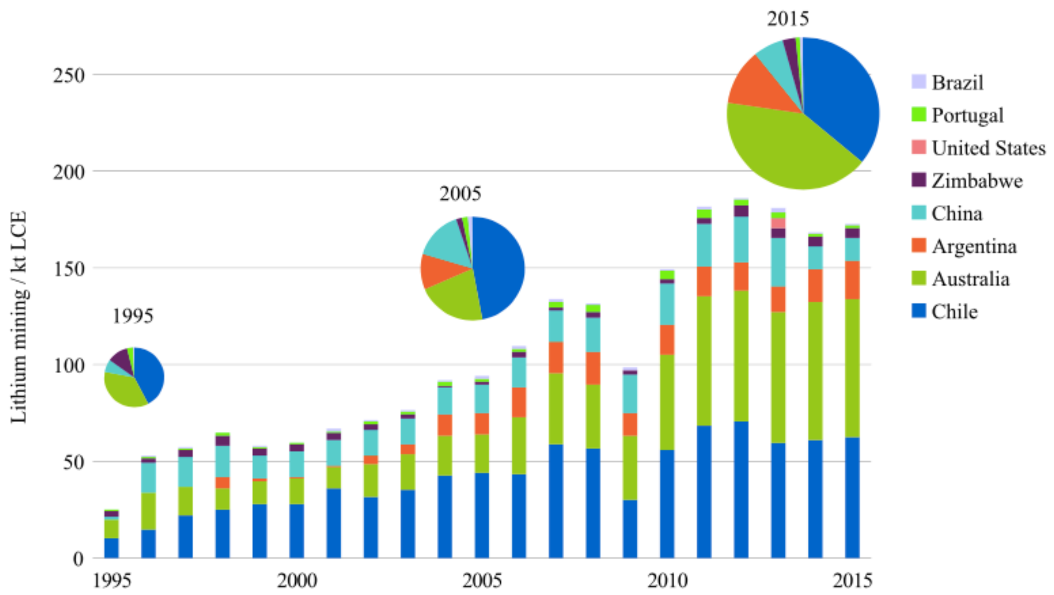


Figure 3: Lithium mining in key countries (Hao et al., 2017).

The European Commission is highly involved in the establishment of targeted measures to secure and improve access to raw materials for the EU. This is is due to the fact that Europe is dependent on imports of metals and metal concentrates, and primary resources from European deposits are not available in sufficient amounts for most metals. Several government reports (Report on Critical Raw Materials 2010; Study on Critical Raw Materials at EU level 2014 and updated version in 2017) have been relased in these years, in which growing concerns over the short-term availability of natural resources and the potential implications for firms are expressed.

In particular, the EC periodically (each 3 years) defines a list of Critical Raw Materials (CRM) that are crucial to Europe's economy.

The methodology followed to carry out the list is based on a criticality assessment at EU level on a wide range of non-energy and non agricultural raw materials.

The 2017 criticality assessment was done for 61 candidate materials.

The main parameters used to determine the criticality of the material for the EU are:

- ✓ **Economic importance** - aims at providing insight about the importance of materials for the EU economy in terms of end-use applications and the value added (VA) for each manufacturing sector.
- ✓ **Supply risk** - reflects the risk of a disruption in the EU supply of the material. It is based on the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects.

In the latest list 27 materials were classified as critical and lithium is not among them, although it is closely monitored and analyzed.

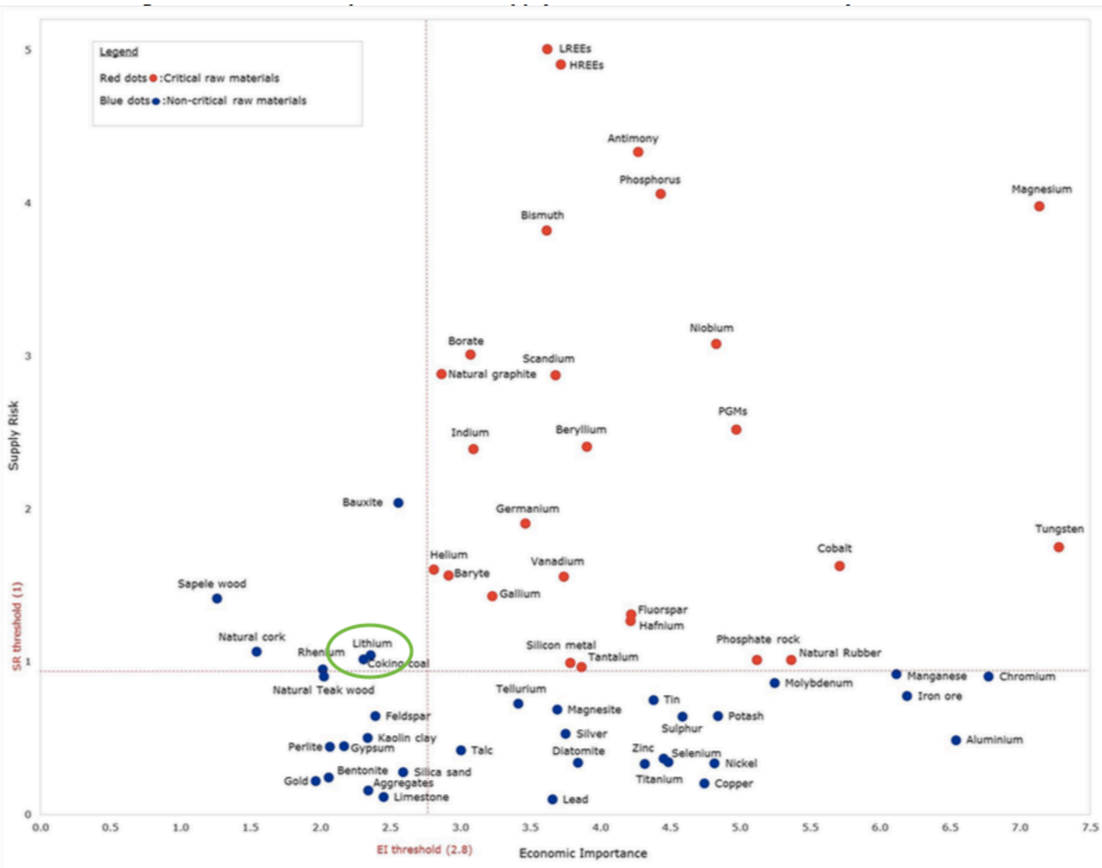


Figure 4: Economic importance & supply risk results of 2017 criticality assessment.

As we can see from Figure 8, lithium is in a borderline position: the Supply Risk threshold is 1 and the lithium supply risk is just above the threshold and the Economic Importance threshold is 2.8 and the lithium economic importance is 2.4.

For now it is not considered as critical but there are a lot of authors that are working on this issue (Grosjean et al., 2012; Kushnir and Sanden, 2012; Kesler et al., 2012; Vikström et al., 2013; Prior et al., 2013; Weil and Ziemann, 2014; Sun et al., 2017; Hao et al., 2017). They are trying to make assessments of world lithium resources and reserves to investigate the overall availability of lithium deposits. The aim of these efforts is to understand if there will be enough lithium on the planet to feed the whole market. Gruber and Medina (2010) underline that there is a problem between different researchers. In fact, total amount of world lithium resources was already assessed by some researchers and organizations who actually did not reach an agreement neither on figures nor on the way to calculate them.

For example, Vikström et al. (2013) establish a total about 31.1 Mt of Li (21.6 Mt of Li in brine deposits, 3.9 Mt of Li in pegmatite deposits, 2 Mt of Li in oilfield and geothermal brines). USGS (2016), instead, establishes that the global known resources of lithium are about 41 million tonnes.

The figure below (Figure 5) tries to give a holistic overview of the distribution of currently known lithium resources (Hao et al., 2017).

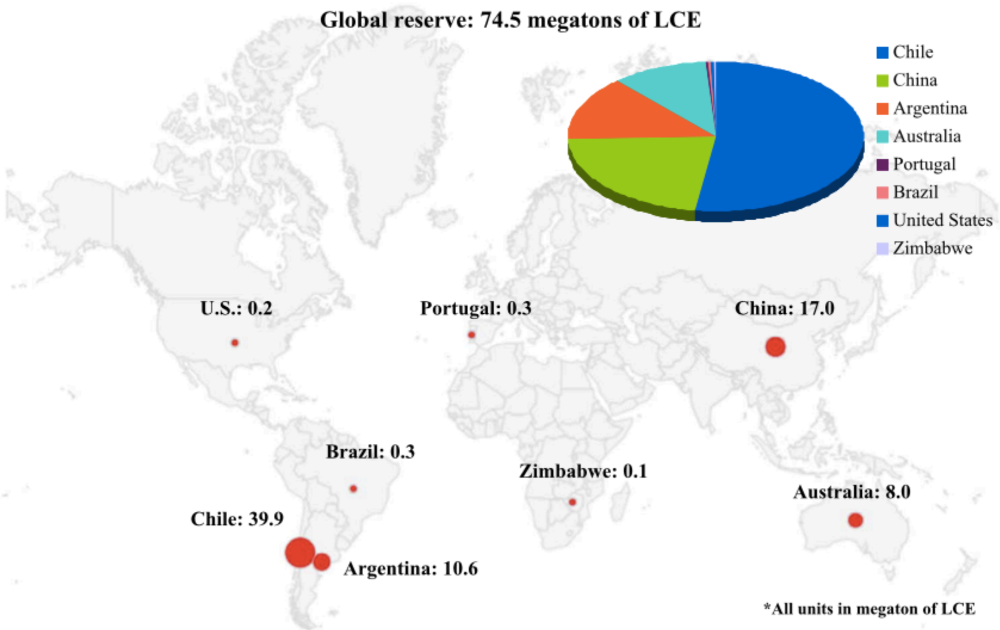


Figure 5: Global distribution of lithium reserves (Hao et al., 2017).

Availability is not the only issue about this material. The biggest amount of lithium is located in the ABC triangle made by Argentina, Bolivia, and Chile. The picture becomes more alarming if we consider that the concentration of about 70% of global brine resources is in just four countries: Argentina, Bolivia, Chile and China (Kesler et al., 2012). In this scenario, the geopolitical aspect acquires huge importance. In fact, in a ipotetical scenario, lithium shortages could threaten the EV market supply since the most directly available resources are currently geographically concentrated. Moreover, another problem is that the scale adaptation of current production facilities appears not reactive enough to follow in real-time a highly probable steep growth in lithium demand and thus new investments are required. Therefore, following the reasoning done, we can conclude that lithium is affected by a problem of accessibility.

To confirmation of this, the analysis of the lithium price (Figure 6) in the last years shows how much the market is unstable and volatile. From a lithium market price of 1.500 $/ton in 2005 to a value of 9.100 $/ton in November 2017.

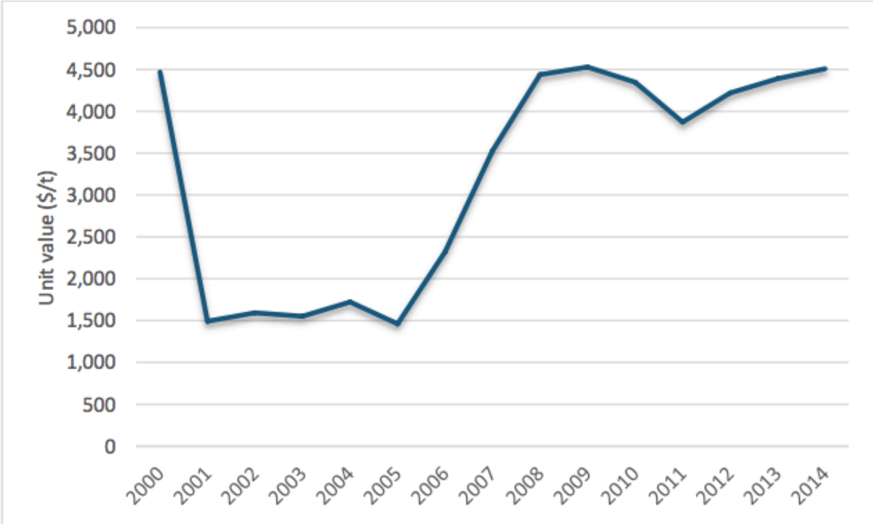


Figure 6: : Lithium price from 2000 to 2014.

Grosjean et al. (2011) provide a quite clear and simple image. Focusing on batteries, considering that a LIB contains 8% Li2CO3 and that packs of batteries will at least weigh 200 kg in future EVs, a minimum of 16 kg of lithium carbonate would be required for each pack of batteries. If the total annual lithium production is 21,300 t, it means that a maximum of 7.1 million packs of batteries can be annually fabricated (If we consider that EV LIB fabrication monopolizes all the market). Nowadays there are more than 1 billion vehicles running in the world and a total of 65 million new vehicles are registered each year.

So, if we consider the market share of 25% for batteries, the lithium is only available for 2 million packs of batteries which now hardly represents 3% of the new vehicle registrations. As a result, the current annual lithium production stands out clearly insufficient to quickly provide a future EV market with LIBs. Therefore, significant opportunities of lithium recovery could exist with EOL lithium-ion batteries recycling.

2.2 Recycling as a material recovery option

One of the options of value recovery is performed through recycling activities.

I decided to focus my attention on this recovery option because by experts (Midema and Moll, 2013; Beheshti and Aune, 2016; Rahman, 2017) recycling is considered the best way to solve the problem of the remarkable quantity of EOL Li-batteries that will be, based on the exponential diffusion of EVs in the following years.

For the other recovery options: reuse option, is not so diffused. Indeed, after a certain level of performance, the LIB can not be reuse for automotive purposes (Richa et al., 2014) and the only remaining application is the storage of electricity from renewable energy sources (Standridge and Hasan, 2015; Alonso and Gallo, 2016). And Finally, disposal is forbidden by laws (Battery Directive, 2006).

Therefore, recycling activities are considered important because they represent the most viable option that allows the exploitation of battery "urban mines". The concept of "urban mines" acquires huge relevance in the last years (Hagelüken, 2014) and it refers to the availability of huge quantity of valuable materials in a small area. The exploitation of this new source of materials is preferred than natural mines since the high concentration of materials embedded in products: for example, in only one lead-acid battery I can extract 8 kg of lead. However, in order to use this potential source of secondary supply, Hagelüken (2014) affirms that some changes will need to take place. For example, a shift from a "waste management" to a "resource management" attitude; a definition of targets with emphasis on the quality and efficiency of recycling processes; and a change in the vision of manufacturers. Rather than a burden imposed by governments, recycling activities can be seen as opportunities for manufacturers to sustainably increase access to the raw materials needed for their future production. Pagell et al. (2007) add that the direct involvement of manufacturers in recycling operations can create important knowledge of products, processes and even customers. Moreover, recycling in addition to being a highly efficient way of reintroducing valuable materials into the economy, it contributes to address key strategic objectives like higher resource efficiency, higher access to raw materials, lower environmental impacts and lower energy intensity of materials supply (Eurometaux, 2013; Hagelüken, 2014). Indeed, recycling activities allow the reduction of the environmental burden that would otherwise occur by preventing emissions from discarded products and landfills into soil, air and water (Li et al., 2016). In addition, less amount of energy demand, carbon dioxide emissions, water and land use are the result of the reduction of mining activities (Hagelüken, 2014).

Furthermore, recycling is a way to secure the supply of materials because it allows to contribute to the reduction of geopolitical dependencies arising in places where critical metal resources are concentrated in a few mining countries and maybe are in the hands of a small number of companies (the case of lithium) (Hagelüken, 2014; Speirs et al., 2014; Andersson, 2016).

A limitation of such activity is that the economy of recycling depends on the materials that have to be collected. Indeed, players perform recycling activities only if they are able to recover the process costs through the selling of recovered materials into the market (Hoyer et al., 2015). Rahimifard et al. (2009) explain that one of the most critical issues for the success of recycling is the availability of markets for the recovered materials. Moreover, Bellmann and Khare (2000) identify the needs to establish a "pull" recycling infrastructure, in which supplier demand for cheaper secondhand materials (compared to the price of virgin materials) can be the driver for the new market. In fact, authors refer to the "chicken and egg" situation, where investment and commitment to recovery of recyclable materials will only be undertaken, if there is a market for the re-processed materials.

Therefore, it is important to recognize secondary materials as a source of new products or value creation, especially when raw material costs increase and recycling technologies improve. In fact, with the right combination of information on material value, technology and creation of new markets, materials previously seen as value-less waste may represent new feed into existing processes or new products (Simpson, 2010).

2.3 Description of CLSC

In the last twenty years, CLSC became a fully recognized subfield of supply chain management (Guide and van Wassenhove, 2009). In fact, based on economic, legal, social and environmental factors, closed-loop supply chain issues have attracted attention among practitioners and academia.

Initially, the growing attention on CLSC issues was born with public awareness (Dowlatshahi, 2000) and governmental legislations that forced producers to take care of their End of Life (EOL) products. Guide and Van Wassenhove (2009) underlined that at the beginning manufacturers saw this closed-loop perspective as a way to minimize costs, but in the last years CLSC is seen as a revenue opportunity.

When we are talking about CLSC we refer to the integration of forward supply chain (FSC) and reverse supply chain (RSC) (Govindan et al., 2014; Guide and van Wassenhove, 2003). A generic form of CLSC is shown in picture 7.

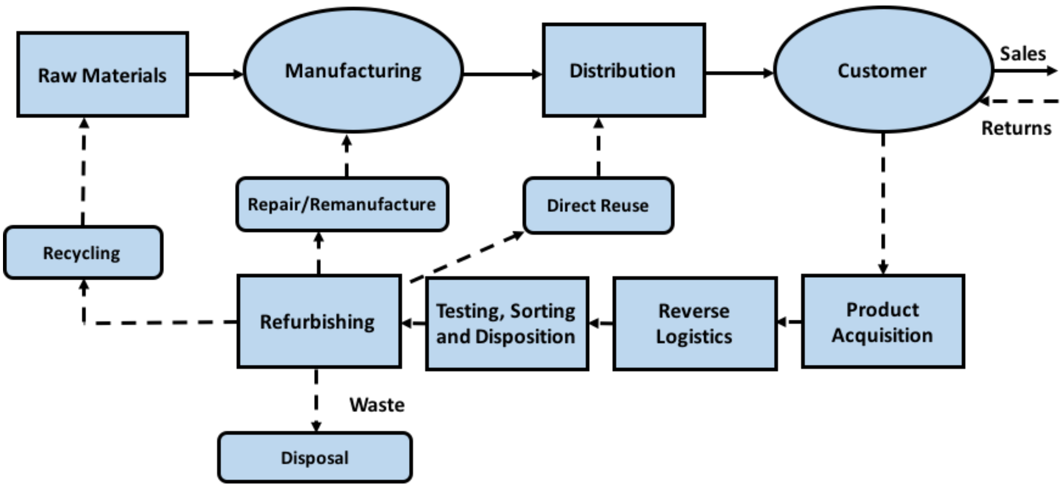


Figure 7: A generic form of forward and reverse SC (Adapted from: Tonanont et al., 2008).

The forward supply chain, the linear model of consumption, is the classical form of the supply chain and it is a combination of processes with the aim to fulfill customers' requests. It includes a wide set of entities like suppliers, manufacturers, transporters, warehouses, retailers and customers themselves (Chopra and Meindl, 2010).

Instead, the reverse supply chain is a set of activities that starts from end users where EOL products are collected and managed according to different decisions undertaken by different actors who are involved in the reverse flow.

The RSC process can be organized sequentially by five key steps (Guide and van Wassenhove, 2003; Prahinski and Kocabasoglu, 2006):

- ✓ **product acquisition** to obtain products from end-users. Example of returns are defective and damaged products, products returns and recalls, discarded products;
- ✓ **reverse logistics** (RL) to move products from the point of use to to the point of disposition for the purposes of capturing value or proper disposal. Activities include transportation, warehousing, distribution and inventory management;
- ✓ **testing, sorting and disposition** to determine the product's condition and the most economically attractive reuse option based on the level of quality of returned product;
- ✓ **refurbishing** to enable the most economically attractive of the options: direct reuse, repair, remanufacture, recycle or disposal;
- ✓ **remarketing** to create and exploit markets for refurbished goods and distribute them to new or secondary markets.

In literature, the papers written by Guide and Van Wassenhove (2009), Stindt and Sahamie (2012), Souza (2013), Govindan et al. (2015) provide a comprehensive literature review of recent papers on reverse logistics and closed-loop supply.

The result provided by Govindan et al. (2015) is that, over the 382 (published between January 2007 and March 2013) papers selected and reviewed, a comprehensive view is missing. Generally, research is concentrated on a specific subject from an independent point of view.

Indeed, there are studies focused on a specific scope (different product returns, reverse logistics network, etc.) and therefore they consider only some particular processes like the product acquisition activities, the RL process or one of the refurbishing options. For example, a lot of authors focused their attention on RL and not CLSC (Carter and Ellram, 1998; Dowlatshahi, 2000; Knemeyer et al., 2002). Others are largely focused on product recovery via remanufacturing and other recovery options like recycling are not considered (Souza, 2013). Therefore, this myopic view of focusing on particular processes does not consider all the possible paths in which a product could be managed. In fact, papers which are focused only on product remanufacturing are losing the option of considering the possibility to recover final value through recycling or according to the other refurbishing options, since each product return need to have its own reverse supply chain in order to be able to optimize its value recovery (Guide and Van Wassenhove, 2003).

Guide and Van Wassenhove (2009) underline that industry and academia rarely consider the RSC as a business process but, they consider it as a series of independent activities, in an isolated perspective without considering its integrated nature. An example of this fragmented perspective is provided by companies which do not actively manage the process of acquiring returns and they passively accept returns from the market/channel. This behavior is the result of the complexity of the market which is affected by uncertainty in quality, quantity and timing of returns.

Moreover, following the CLSC perspective, studies found that less than the 30% of all products are designed with disassembly and recycling process in mind (McDonough & Braungart, 2002). This is the evidence of an important issue that affects companies nowadays: how to deal with EOL products that are difficult to recycle. Only when managers understand the relationship between products creation and products take-back, they will have less problems in performing CLSC activities (Pagell et al., 2006).

Indeed, in the long terms, companies by the controlling of product take-back can have benefits in terms of risk hedging of materials (commodity price, materials availability). Highly unstable prices in commodities markets can put pressure on producers. For this reason, manufacturers should strategically manage virgin materials and recycled materials in order to use the materials from products take-back when the market price is high (Ellen MacArthur Foundation and McKinsey & Company, 2014).

Finally, Simpson (2010) says that companies are trying to develop alternative and innovative ways to find non-landfill and financially viable disposal options for EOL products. This happens through collaboration with other firms. Collaboration between supply chain partners may provide the solution to sourcing of recycling solutions. In fact, the interactions or networking between members of the supply chain can create "recycling relationships" that generate new markets or disposal solutions for recyclables. For example, some firms (e.g. Panasonic) have created recycling system to handle products from many electronics manufacturers, including their competitors (Lytle, 2003). The large volume and the variety of returned products have not only created economies of scale, but allowed companies to innovate their processes to handle returns in more environmental ways. This practice of simultaneously recycling their own products and providing recycling services to others has proven to be a profitable business.

In conclusion, in my thesis, when I use CLSC, I refer to the definition provided by Guide and Van Wassenhove (2009). They defined that CLSC management is *the design, control, and operation of a system to maximize value creation over the entire* *life cycle of a product with dynamic recovery of value from different types and volumes of returns over time*.

2.4 CLSC in the automotive battery industry

Focusing on the literature of automotive battery industry, in Table 1 there is a list of key publications that deal with RL, RSC, CLSC and different recovery processes.

The selected papers are quite recent (from 2010 to 2017) in order to provide a picture of the current research situation. Moreover, since my work is focused on the analysis of lead-acid and lithium-ion batteries, I selected papers which are focused both on them.

Authors, who focus their attention on batteries RL (Kannan et al., 2010; Subulan et al., 2015a), are interested in the definition of reverse logistics network designs to support different recovery options. Subulan et al. (2015a) developed a SC network design model which could be applicable for remanufacturing/refurbishment activities in case of batteries with high recoverable value and long life cycles. The novelty of this network is the definition of a new objective namely "maximization of the collection of returned batteries covered by the opened facilities". In fact, in contrast to the existing multi-objective CLSC network design models which are cost or profit oriented, new flexibility objectives are introduced due to the nature of reverse flows.

Instead, Kannan et al. (2010), based on the great pressure on products take-back legislation, setup a logistics network with the focus on recycling activities in order to exploit the valuable materials embedded in products. These authors are pushing a lot of effort on this topic because RL is defined an important step for reaching sustainability: economic and also environmental sustainability (Lee et al., 2010). Moreover, the effective and efficient implementation of RL activities can allow battery manufacturers to increase their customer service level and reduce their costs such as collection, inventory and transportation costs (Subulan et al., 2014).

For what concern papers about automotive battery RSC, authors (Rahman and Subramanian, 2012; Richa et al., 2014; Hagelüken, 2014; Gaines, 2014; Standridge and Hasan, 2015) are especially interested in defining a proper working reverse system able to manage the EOL batteries from final customers to recyclers (see definition of RSC).

For example, there are authors like Gaines (2014), who tries to define a working system for the correct performing of recycling activities for LIBs. In fact, since the volume of EOL lithium-ion batteries is very low now, she claims that there is the opportunity to obviate some of the technical, economic, and institutional roadblocks that may arise in future.

Finally, about battery CLSC, the focus is on defining solution of loop-closing in particular for LIB. For example, studies of Subulan et al. (2015) and Richa et al. (2017) are focused on analyzing ways to define valuable metal recovery options from LIB batteries. The results show that direct and cascaded reuse, followed by recycling, can together allow to achieve both environmental and economic benefits. Moreover, battery life cycle analysis is defined a fundamental aspect to take into consideration for the identification of policies and mechanisms able to increase the feasibility of the system (Richa et al., 2017).

In Table 1 there is a list of authors that deal with the automotive battery industry focusing or on RL, RSC, CLSC and recovery processes.

Table 1: Authors that deal with automotive battery industry focusing on RL/RSC/CLSC and recovery processes.

Automotive Battery Industry	
Scope	Source
RL	Kannan et al. (2010); Rahman (2014); Subulan et al. (2015a).
RSC	Rahman and Subramanian (2012); Richa et al. (2014); Hagelüken (2014); Gaines (2014); Standridge and Hasan (2015).
CLSC	Schultmann et al. (2006); Gratz et al. (2014); Subulan et al. (2015b); Richa et al. (2017).
Recovery process	Idjis et al. (2013); Zeng et al. (2014); Chen et al. (2014); Wang et al. (2014); Jayant et al. (2014); Standridge and Corneal (2014); Wang et al. (2014); Hoyer et al. (2015); Standridge and Hasan (2015); Hanisch et al. (2015); Zhang et al. (2016); Alonso et al. (2016); Davidson et al. (2016); Li and Liu (2016); Beheshti and Aune (2016); Swain (2016); Heelan et al. (2016); Wang and Zhang (2016); Engel and Macht (2016); Idjis and Da Costa (2017); Rahman and Afroz (2017).

Following the same focus (automotive battery industry, LIB and LAB), in Table 2, it is provided a list of authors classified according to the different reverse supply chain activities that they deal with in their papers: reuse, remanufacture/repair, recycle and dispose.

As we can see, reuse and dispose options are activities managed by a small number of authors especially because, for automotive batteries, the direct disposal is an activity that is no longer performed (2006/66/EC). In fact, thanks to the recycling activities there is the possibility to recover materials and gain money from the selling of them as new source of supply. Moreover, the introduction of environmental regulations governs the management of these EOL products reducing or avoiding at all the landfilling.

In the last years, instead, the reuse activity is acquiring huge relevance for the possibility to use used EOL batteries for the storage of renewable energy from sun and wind in order to exploit the residual power of the automotive batteries (Standridge and Hasan, 2015; Richa et al., 2017). In fact, the same Standridge and Hasan (2015) explain how EOL batteries are more used for energy storage purposes instead of reusing in other vehicles.

Automotive battery remanufacturing, it is not so interesting for authors. Standridge and Corneal (2014), and Standridge and Hasan (2015) mentioned the replacement of damaged cells within the battery as an effective remanufacturing strategy but any further analysis was performed.

In the last years, the research based on automotive battery recovery options is concentrated on recycling. In this case, the list of authors that deal with battery recycling would be longer; in Table 2 there are only some of the most representatives for findings and topics managed.

Authors, in their analysis, are more focused on dealing with a specific aspect of the recycling activity: Jayant et al. (2014) provide a model and a network for a correct implementation of batteries recycling, Kieckhafer et al. (2014) are focused on recycling technology and capacity planning issues, Zeng et al. (2014), Hagelüken (2014), Li and Liu (2016), Rahman (2017) evaluate different technological process to recycle automotive batteries. Moreover, there are authors (Wang et al., 2016) that describe studies about the definition of new recycling processes able to recover with new and particular technologies valuable materials that so far they were not extracted.

The result after the analysis of papers about recycling is that when authors deal with recycling activities two perspectives can be considered: who deal with recycling with the focus on manufacturer decisions and implications (Kannan et al., 2010; Jayant et al., 2014; Davidson et al., 2015; Zeng et al., 2014; Hanisch et al, 2015), and who deal with recycling with the focus on recyclers (Hagelüken, 2014; Zeng et al., 2014; Linda, 2014; Li and Liu, 2016; Beheshti and Aune, 2016; Engel and Macht, 2016).

Following the manufacturer perspective, authors are more interested in the different typologies of battery design (Zeng et al., 2014; Hanisch et al, 2015), in the classification of design for X activities (Design for Disassembly, Design for Reuse, Desing for Recycle, etc.) that manufacturers decide to implement and in the definition of the life cycle assessment of different types of automotive batteries (Richa et al., 2014; Davidson et al., 2015). Moreover, authors are interested in analyzing ways in which companies can fulfil their responsibility for managing EOL products after the introduction of the EPR (Kannan et al., 2010; Jayant et al., 2014).

Instead, if the focus is on recyclers the major topics are focused on the description of recycling technologies for particular types of battery (Hagelüken, 2014; Linda, 2014; Li and Liu, 2016) and on the comparison between activities and performances of different recycling processes (Zeng et al., 2014; Beheshti and Aune, 2016; Engel and Macht, 2016). For example, Zhang et al. (2016), through the comparison of different recycling technologies, are interested in the definition of levels of energy requirements and environmental pollution of different technologies since the growing pressure to achieve sustainable greener recycling methods.

The result is that the literature on automotive battery industry is largely focused on different ways of recovery of automotive batteries rather than the examination of a larger system such as RSC or CLSC.

The most analyzed activity is recycling that is able to provide both economic and environmental benefits. Moreover, based on the exponential increase of EVs and the issue of material availability, authors are concentrated to review the existing recycling technologies in order to identify enablers and criticalities related to the recovery of valuable materials like lead, cobalt, lithium and others. Especially the focus is on lithium since so far there is not a recycling technology able to recover this material in an efficient and effective way. Therefore, a lot of authors when dealing with recycling they also refer to the lithium availability issue (Wang et al, 2014; Subulan et al., 2015a; Swain, 2016).

Table 2: List of authors that deal with RSC activities.

Automotive Battery Industry	
Reverse supply chain activities	Source
Reuse	Standridge and Corneal (2014); Standridge and Hasan (2015); Alonso et al. (2016); Idjis and Da Costa (2017); Richa et al (2017).
Remanufacture/Repair	Standridge and Corneal (2014); Standridge and Hasan (2015); Zhang et al. (2016); Richa et al (2017).
Recycle	Kannan et al. (2010); Idjis et al. (2013); Wang et al. (2014); Zeng et al. (2014); Chen et al. (2014); Standridge and Corneal (2014); Hagelüken (2014); Gratz et al. (2014); Gaines (2014); Wang et al. (2014); Jayant et al. (2014); Hoyer et al. (2015); Standridge and Hasan (2015); Hanisch et al. (2015); Subulan et al. (2015a); Davidson et al. (2016); Zhang et al. (2016); Li and Liu (2016); Alonso et al. (2016); Beheshti and Aune (2016); Swain (2016); Heelan et al. (2016); Wang and Zhang (2016); Engel and Macht (2016); Cornado et al. (2017); Richa et al. (2017); Rahman and Afroz (2017); Idjis and Da Costa (2017).
Dispose	Richa et al. (2014).

2.5 Overview of frameworks of factors

In order to analyze in a comprehensive way the automotive battery industry (focus on LABs and LIBs) in a CLSC perspective, a framework is needed.

The literature offers different set of factors that influence the development of a closed loop system. The different frameworks are characterized by different number and types of factors and different focuses of analysis due to the variety of perspectives taken (CLSC, RL, RSC, recycling activity). In fact, each framework was developed to answer to a particular scope such as CLSC for PV panels (Besiou and Van Wassenhove, 2016), RL in the electronic industry of China (Lau and Wang, 2009), how to perform effective and efficient recycling (Hagelüken, 2014).

Therefore, I decided to select the most representatives in terms of considerations and findings and among them those dealing with technological products in order to have similarities with automotive batteries (Photovoltaic panels (Guide and Van Wassenhove, 2016); EOL computers (Rahman and Subramanian, (2012); electronic industry (Lau and Wang, 2009)).

A short summary of these framework is provided in Table 3.

Among the papers analyzed, there are research that describe frameworks based on the CLSC but focused on a particular perspective. For example, Rahman and Subramanian (2012) are focused on the manufacturer perspective in order to define how remanufacture a product (e.g.). Moreover, there is a study that analyzed the incentives that the OEM can achieve with the introduction of a remanufactured product in its own system (Pagell et al., 2006; Souza, 2013). Other frameworks, instead, are focused on the recycling of a specific metal (lead, nickel, aluminum), or based on the recycling of specific products like electronic waste (Tanskanen, 2013). Since their limitative perspective, these approaches do not consider possible interactions with other players in the supply chain.

In fact, in a CLSC there is the involvement of a huge variety of actors (manufacturers, recyclers, collectros, etc.) who perform different activities. In literature, there are only few studies that take into consideration this aspect. In their papers (Knemeyer et al., 2002; Besiou and Van Wassenhove, 2016), authors underline that there is a high degree of complexity between the interaction of different players since each of them want to achieve its own objectives.

Finally, there are some papers published in the last years, which define a framework to apply in order to study the CLSC (or its sub-systems) and managed the different recovery options. Each paper is focused on particular products like PV panels and wind turbines (Besiou and Van Wassenhove, 2016), computers (Rahman and Subramanian, 2012) and WEEE (Lau and Wang, 2009). Instead, Lapko et al. (forthcoming) provide a framework not on CLSC for a particular product but focusing on critical raw materials.

In the classifications analyzed, the majority of the authors subdivide factors in macro categories like internal and external (considering the company's bounderies) (Carter and Ellram, 1998; Besiou and Wassenhove, 2016) or strategic versus operational (Dowlatshahi, 2000; Souza, 2013) or, for example, Lau and Wang (2009) combine the previous classifications and they identify external and internal factors, where the latter are further classified in strategic and operational factors.

Based on all the classifications, the most considered factors are those related to regulatory, financial, technological and company relational issues.

In table 3 we see that authors can use the same name to refer to the same factor like "legislation" (Lau and Wang, 2009; Souza, 2013; Lapko et al., forthcoming; Rahman and Subramanian, 2012) or they can use different name. For example, for the technological issue, based on the specific scope of the analysis, they use "design activities" (Besiou and Van Wassenhove, 2016), "remanufacturing and recycling" (Dowlatshahi, 2000), "technological requirements" (Lau and Wang, 2009), "technical feasibility of recycling" (Lapko et al., forthcoming), "technical recyclability of the material or metal combination" (Hagelüken, 2014), "accessibility of the relevant components" (Hagelüken, 2014).

Moreover, when authors have to define factors related to the company relational issues, or they use only one factor like "Integration and coordination" (Rahman and Subramanian, 2012) or they define different shadows like "Engagement of supply chain actors", "information exchange and supply chain transparency", "competition" (Lapko et al., forthcoming).

Some limitations are present in the papers analyzed. First of all, the different lists of factors need to be considered focusing on the scope of each analysis because the factors that are relevant for the author, they could not be suitable for my purposes. For example, the factors "top management support" (Carter and Ellram, 1998), "policy entrepreneurs" (Carter and Ellram, 1998), "transportation" (Dowlatshahi, 2000), "packaging" (Dowlatshahi, 2000), "customer demand" (Rahman and Subramanian, 2012) are factors that in my analysis are not investigated since their high level of detail.

In same frameworks a holistic view is missing. Although the paper written by Hagelüken (2014) is focused on defining effective and efficient recycling activities for both products and materials, it fails in studying the different relationships between different actors belonging to the CLSC. Moreover, some authors focused their attention only on some of the actors involved in the supply chain and thus missing the entire view of the supply chain and the possible interactions among actors. For example, Carter and Ellram (1998), Dowlatshahi (2000), Lau and Wang (2009) and Souza (2013) focused their analysis on the manufacturer perspective.

The paper of Souza (2013), although it is focused on CLSC implementation, it is focused only on strategic and tactical issues. The operational dimension related to the "disassembly planning" (e.g. sequence and depth of disassembly) and the operational decisions of recovery are not discussed. Moreover, in the paper is considered only the case in which manufacturer decides to remanufacture the product and the other recovery options are not taken into account.

Therefore, since the scope of each individual publication is still limited by the perspective taken and the list of factors considered, I decided to study the different perspectives taken by the different scholars in order to define a comprehensive list of factors useful to describe the battery systems. The papers written by Besiou and Van Wassenhove (2016) and Lapko et al. (forthcoming) are those from which I take the most important insights since they provide a framework for the proper implementation of a CLSC focusing on recycling as recovery option.

The former is one of the first studies that deal with CLSC for a specific product (Photovoltaic panels) and the framework provides a well-structured classification of external and internal factors. Furthermore, the internal factors are classified between those that are within the control of the industry and those within the control of the individual company. The latter study, instead, focusing on the material perspective it is important because it presents a framework that allows to identify enabling and bottleneck conditions for the implementation of a CLSC for critical raw materials.

Moreover, another important aspect of these two papers is that they consider how the factors manifest themselves on different companies along the supply chain (manufacturers, collectors and recyclers).

The table below summarize all the frameworks analyzed in terms of scope and list of factors.

Table 3: List of frameworks analysed with scope and list of factors.

Reference	Scope	List of factors
Carter and Ellram (1998)	RL (product)	Regulations; Customers; Quality of inputs; Vertical coordination; Stakeholder commitment; Top management support; Policy entrepreneurs; Incentive systems.
Besiou and Van Wassenhove (2015)	CLSC (product)	Regulations; Collective schemes; Competition; product life cycle; Design activities; Individual schemes.
Dowlatshahi (2000)	RL (product)	Strategic costs; Overall quality; Customer service; Environmental concerns; Legislative concerns; Cost-benefit analysis; Transportation; warehousing; Supply management; Remanufacturing and recycling; Packaging.
Lau and Wang (2009)	RL (product)	Awareness; Legislation; Economics; Systems; Collaboration; Strategic significance; Financial considerations; Managerial skills; Technological requirements.
Souza (2013)	CLSC (product)	Network design; Collection strategy; Leasing/selling; Supply chain coordination; Take-back legislation; Impact of recovery activities; Product returns; Returns disposition.
Lapko et al. (forthcoming)	CLSC (materials)	Availability of items for recycling; Technical feasibility of recycling; Economic feasibility; Market for recycled materials; Engagement of supply chain actors; Established industrial infrastructure; Information exchange and supply chain transparency; Competition; Legislation; Public awareness.
Rahman and Subramanian (2012)	RSC (product)	Legislation; Customer demand; Strategic cost/benefit; Environmental concern; Volume and Quality; Incentive; Resource; Integration and coordination.
Hagelüken (2014)	Recycling (materials)	Technical recyclability of the material or metal combination; Accessibility of the relevant components; Economic viability; Collection mechanism; Entry into the recycling chain and remaining therein up to the final step; Optimal technical and organizational setup of this recycling chain; Sufficient capacity along the entire chain.

2.6 Definition of factors

Taking into consideration all the lists of factors defined by the authors cited in the section before and since among selected papers neither is focused on both CLSC and battery system, I decided to define a new list of factors.

More precisely, I reported some factors as defined by previous authors without modifying the meaning (*Legislation* F3, *Infrastructure* F5, *Financial Aspects* F7) since they refer to aspects with general applicability. For example, a company when it decides to perform business activities, it has to consider as fundamental dimension of analysis the economic perspective (F7). Moreover, F3 is not change because I use the same perspective of other authors in dealing with regulations.

Others factors or they have been joined together like *Technological Aspects* (F1) that considers both product design and recycling technology, since in the battery system the two dimensions are interrelated, or they have been separated like *Volume* (F2) and *Quality* (F8) to better fit the purpose of my analysis. In fact, in order to implement CLSC, it is not only necessary to have a considerable flow of recycled materials but also the secondary materials need to have high level of quality (e.g. purity). Since these two dimensions are not connected each other: it could happen that huge volume of EOL products are present but the quality after the recovery is very low. In this way, with the separation of the factors it is possible to perform a more in depth analysis.

The novelty of the list is not in the contents of the factors but in the way in which they are defined.

The aim of this list of factors is the possibility to provide a comprehensive view of CLSC to apply for the battery industry. All these factors will be used as reference dimensions in the following analysis in order to define the critical success factors in terms of barriers and enables both for the lead-acid battery system and the lithium-ion battery system.

The description and the distribution of the factors in the analyzed literature is presented in Table 5.

The result of my analysis is a list of 8 factors which is presented in the table below (Table 4).

Table 4: My list of factors.

Code of Factor	Name of Factor
F1	TECHNOLOGICAL ASPECTS
F2	VOLUME
F3	LEGISLATION
F4	ORGANIZATIONAL SET UP
F5	INFRASTRUCTURE
F6	COMPANIES INTERACTIONS
F7	FINANCIAL ASPECTS
F8	QUALITY

Table 5: Distribution of factors in literature.

	(Guide and Van Wassenhove, 2001)	(Ferguson and Toktay, 2006)	(Rahimifard et al., 2009)	(Dowlatshahi, 2000)	(Lau and Wang, 2009)	(Rahman et al., 2012)	(Janse et al., 2010)	(Carter and Ellram, 1998)	(Stock, 1992)	(Govindan et al., 2014)	(Souza, 2013)	(Lapko et al., forthcoming)	(Besiou and Van Wassenhove, 2016)	(Simpson, 2010)	(Pagell et al., 2007)	(Eurometaux, 2013)	(Hagelüken, 2014)
Scope*	Prod. Reco.	Prod. Reco.	Prod Recy.	RL	RL	RL	RL	RL	RL	RL CLSC	CLSC	CLSC	CLSC	Recy. Man.	Recy. Man.	Recy. Sys.	Recy. Sys.
F1 – TECHNOLOGICAL ASPECTS		x	x	x	x		x		x	x	x	x	x		x	x	x
F2 – VOLUME	x	x	x		x	x	x		x			x	x	x		x	x
F3 – LEGISLATION	x		x	x	x	x		x			x	x	x			x	x
F4 – ORGANIZATIONAL SET UP					x			x		x	x		x	x	x		x
F5 – INFRASTRUCTURE	x		x	x	x		x		x	x	x	x		x		x	x
F6 – COMPANIES INTERACTIONS		x			x	x	x				x	x		x	x	x	
F7 – FINANCIAL ASPECTS	x	x	x	x	x	x	x		x			x	x	x	x	x	x
F8 – QUALITY	x		x			x		x	x			x	x				x

*Prod. Reco. – Product Recovery; Prod. Recy. – Product Recycling; RL – Reverse Logistics System; CLSC – Closed Loop Supply Chain; Recy. Man. – Recycling (Manufacturer perspective); Recy. Sys. – Recycling System

2.6.1 F1 - Technological Aspects

The technological aspects are the typical internal factors within the control of the industry of the individual company. They refer to aspects related to the battery product design and to the availability of technologies to perform a proper recycling activity.

Sometimes, in the frameworks analyzed, some authors considered only aspects related to the product design in terms of physical and chemical compositions, others made considerations about the ease of performing recycling activities according to the different recycling technologies and others tried to combine the two dimensions.

Hagelüken (2014) says that manufacturers have to face different issues as product configuration, use of different materials and components, accessibility to materials, ease of dismantling. Besiou and Van Wassenhove (2016) support that in order to perform an effective recycling, manufacturers have to think about these issues during the design phase of the product so they can anticipate those issues that could be critical in future. Moreover, Rahimifard et al. (2009) underline that in order to reach a sustainable EOL product recovery, designers need to have an appreciation for the current technologies and market trends driving the reclamation sector in terms of recycling practices and market values of recycled materials. This because designers of products with relatively long-life spans (i.e. 10 years) would find it difficult to justify selection of a particular 'design for X' paradigm at the early stages of development, given the changes in end-of-life processing technologies during an extended period of time. To solve this problem, it could happen that the same battery manufacturer can internally create a part in charge of the recycling activities.

The variety of battery designs affect the recycling activities since each recycling process (e.g. thermal, pyro-metallurgical, hydrometallurgical) have specific requirements to fulfill and the wrong battery could cause serious security and safety problems (Gaines, 2014; Hanisch et al., 2015).

In the market, there are both different battery designs and different recycling technologies. The different battery designs are the results of the decisions taken by the different manufacturers in order to satisfy customer needs in terms of performances, weight, and size. In fact, thanks to the physical properties of lithium (light and easy to work) and the combination of materials used for cathodes and anodes, battery manufacturers can create a huge variety of batteries. Instead, the different battery recycling technologies are driven by the purpose of the recycler. For example, if he wants to recover only valuable materials with lower production costs, he will perform pyro-metallurgical processes (Pagell et al., 2007; Govindan et al., 2014; Besiou and Van Wassenhove, 2016); instead, if he wants to recover lithium embedded in battery, he will use the hydrometallurgical recycling process, a very expensive technology (Gaines, 2014).

2.6.2 F2 - Volume

This factor refers to the availability of EOL products (as the input of the RSC) and the availability of recycled materials (as the output of the RSC and therefore, the new input of a new SC in the CLSC perspective). Thanks to the recycling processes, it is possible to recover materials that could be reused for the production of new products.

The volume of return products is critical for the implementation of RSC (Carter and Ellram, 1998). Closing the loop becomes a feasible solution when there are enough and constant flows of EOL products that feed the recycling process and after that, there are flows of recovered materials that are reused for the production of the same product. With stable and remarkable flows recyclers can achieve economies of scale and they can justify the investments done in performing activities in the RSC (Rahimifard et al., 2009), otherwise they will lose money. Therefore, volume becomes a fundamental factor in CLSC and different authors focused on this with different nuances. Since the focus is on the possibility to use the recovered materials to produce the same product, the factor considers only EOL batteries that will become new batteries. Taking into consideration this focus, some authors like Lau and Wang (2009) explain how the volume of EOL products is characterized by high uncertainty. In fact, the rate of returned products is affected by different factors like the life cycle of the product, the rules set by governments (Battery Directive, 2006) or the incorrect behaviors of customers. Customers could manage EOL products in wrong ways (Hagelüken, 2014; Eurometaux, 2013). In fact, too many EOL products which have valuable materials are landfilled of incinerated. This means a wastage of our urban mine and therefore a low volume of batteries to recycle.

The volume is also affected by the flow of products that are shipped out of EU where there are countries that buy these products due to the high intrinsic value of certain scrap and the embedded energy content (Eurometaux, 2013). Externalization of social and environmental costs hazardous substances leads to unfair cost advantages. Therefore, in some cases, valuable materials are exported illegally with an uncertain quality of recycling of the exported waste.

This factor is relevant because affects the stability of players that decide to perform activities in the reverse supply chain.

Moreover, the volume of recycled material is a fundamental aspect for the right implementation of CLSC. This flow of second-hand material becomes a new important source of supply for battery producers that maybe until now they have bought only mined materials. Simpson (2010) underline that a common practice of recycling firms is to accept for recycling only products which contain materials that for sure will buy as a new source of supply by manufacturers.

2.6.3 F3 – Legislation

The government legislations refer to directives, policies and regulations set by authorities for different actors along the supply chain (e.g. mandatory certifications of recycling activities; incentives and recycling targets; take back legislations).

This factor is present in the majority of frameworks analyzed and it represents the factor that forces companies to behave in a close loop perspective. Regulations are one of the main driver for firm environmental efforts (Rahman et al., 2012). The major aim of these regulations is to protect the environment, avoid landfill and prevent contamination of air and water.

In EU, South Korea and Japan (Dempsey et al., 2010) regulatory measures seek to incentivize producers to design easier-to-recover products (Besiou and Van Wassenhove, 2016). Moreover, regulations ensure firms take back and reuse the products they produce (Dowlatshahi, 2000) or companies have to pay other actors for recovery at EOL (Rahimifard et al., 2009; Souza, 2013; Govindan et al., 2015). These efforts can allow effective material usage, better product creation, improved product yields.

Legislations were the starting point that force companies that produce batteries to think in a close loop perspective. When a company decides to produce and sell a battery in the market, it has to be aware that it will have to care about the managing of the same battery at the EOL according to the EPR (Batteries Directive, 2006/66/EC).

2.6.4 F4 - Organizational set up

The factor is related to the network structure and the set of companies involved along the SC with their different modes of operations and different level of responsibility.

In fact, each company has different degrees of responsibility about the management of products along the SC. For example, the manufacturer of batteries has to care about processes needed to manage the EOL of products according to the Extended Producer Responsibility legislation (Pagell et al., 2007). The EPR is defined as an obligation that manufacturers have to accomplish in order to fulfill their responsibility on the collection and the recovery of their products sold into the market that reach the EOL (Battery

Directive, 2006). Indeed, according to the set of mandatory requirements set by the EC, companies must be aware that if they decide to produce and sell a product, they are forced to pay for its recovery. Manufacturers can decide to perform this type of activities internally but it is a decision that requires huge investments in infrastructure (F5 and F7) or they can decide to share costs and responsibilities with other companies along the SC. In the last case the involvements of the single company is very limited since through the payment of a fee, logistic providers will perform the collection activities and recyclers the recovery activities.

In the Batteries Directive (2006/66/EC) there are reported the rules needed to define the network structure. In fact, based on the decision of companies, they can decide to fulfill their responsibilities individually (Individual Producer Responsibility, IPR) or by joining a collective scheme (Collective Producer Responsibility) (Besiou and Van Wassenhove, 2016). The CPR is the most common solution adopted by battery manufacturers since it allows to exploit synergies and to overcome the logistics difficulties in performing such activities (Souza, 2013). The sharing of the infrastructure among companies ensures efficiency, effectiveness and moreover, it allows the collectors to reach economies of scale.

2.6.5 F5 - Infrastructure

The infrastructure (also in terms of geographic proximity) is defined as the means through which is possible to perform a success CLSC. This factor refers to the availability of enough means, facilities, capacity and right technologies in order to allow the performing of collection, sorting, mechanical and metallurgical processing. All together these elements ensure that EOL products are available for recycling.

In the case in which the collection mechanisms are not in place, it means that products may end up being stored in house-holds or discarded into the waste bin for landfill or municipal incineration (Hagelüken, 2014). In this case the lack of an infrastructure and the wrong behaviors will affect the volume of EOL products to recycle and the related financial flows.

This factor is analysed in few papers. Dowlatshahi (2000) and Hagelüken (2014) emphasize the importance of infrastructure as the mean through which a right closed loop supply chain could be implemented. The right definition of the collecting infrastructure is fundamental to ensure a remarkable EOL volume of products to manage. The combination of different facilities, different actors involved and different activities (transportation, warehousing, etc.) needs to follows the basic logistics rule of right time, right place and right quantity.

Moreover, producers in order to fulfill the government requirements can comply either individually or by joining an approved collective scheme (e.g. European Recycling Platform, 2003). Therefore, the sharing of the infrastructure affects relationships between companies. Firms that decide to use the same infrastructure have to coordinate their reverse logistics activities with transportation modes, inbound and outbound transportation services, networks and loads in order to obtain the greatest benefits (Dowlatshahi, 2000).

2.6.6 F6 - Companies interactions

Pursuing CLSC activities means put together different supply chain actors. This create the definition of different relationships among companies at several levels and for multiple purposes. Therefore, with this factor I want to define the different interactions that companies create in pursuit the close loop perspective as collaboration, cooperation for the purpose of sharing information, knowledge and infrastructures and competition.

The majority of the authors take into consideration this factor but the perspectives taken are different. Lau and Wang (2009) indicate opportunities for collaborations between manufacturers in CLSC with competitors from forward SC. This collaborative approach is more effective and efficient since it allows to reduce the investment of individual firms and to enable economies of scale through centralization. In fact, firms that normally compete against one another in the forward SC may benefit financially and competitively by collaborating in the reverse supply chain.

Rahman et al. (2012) support that interaction between companies allows coordination. In this way coordination of reverse supply chain and integration of information support system would increase the speed of recovery and profitability of the firms. Janse et al. (2010) underline the importance of information sharing between different companies. In the RL information are useful to track and trace product returns, to forecast return products and for inventory management. Companies that have control on EOL products can increase the viability of the reverse supply chain process.

Another aspect to take into consideration is competition. Lapko et al. (forthcoming) define how competition can differ between different actors involved in the CLSC. Lau and Wang (2009) and Simpson (2010) indicate the existence of collaboration even among competitors. Indeed, manufacturers, which generally compete in the FSC, in order to fulfill their responsibility can decide to collaborate in the RSC. In addition, Besiou and Van Wassenhove (2016) underline the positive meaning of competition: between recyclers, the results of competition are lower recycling prices and better service quality.

Finally, transparency must be enhanced across the value chain (Eurometaux, 2013). All flows should be better measured and monitored, across the entire recycling chain, from collection to the final material recovery. This would minimize leakages and contribute to better enforcement of existing collection and recovery/recycling obligations. Simpson (2010), with the analysis of same case studies, claims that supply relationships arise due to the pressure in the market, which encouraged some firms to develop alternative and innovative ways to find non-landfill and financially viable disposal options for returned product, recyclables and waste. Through collaborative relationships, companies can define new solution to sourcing of financially beneficial and innovative recycling solutions.

2.6.7 F7 – Financial Aspects

This factor refers to the overall financial flows related to the activities that contribute to the close loop perspective. It considers the cost/benefits analysis and the presence of economic incentives (e.g. investments in infrastructures, in technologies, in personnel and in products design activities; costs of collection; costs of the recycling process; value of second-hand materials).

This factor is considered in the majority of frameworks described before because the recycling activities are driven by the market value of the recovered materials (Rahimifard et al., 2009). In fact, recovery happens if the overall economics benefits of recycling can be recognized by companies (Hagelüken, 2014).

The economic dimension is fundamental and Dowlatshahi (2000) defines the close loop supply chain as a way for the companies to make profits with the possibility to have strategic costs savings. Through its costing system, the firm should establish the cost-benefit structure so that it can define the overall costs and benefits related to the choice of remanufactured or recycled products compared to the disposal or landfill costs. Guide and Van Wassenhove (2001) were one of the first to introduce the idea of product acquisition management where the OEM can control the product returns through appropriate economic incentives in order to have price advantages on second-hand materials. Ferguson and Toktay (2006) and Govindan et al. (2014) state that the right incentive mechanisms would enhance the RL success in order to increase the recovery activities profitability. Lau and Wang (2009) underline that recycling activities allow to enhance the green corporate image of companies and therefore, manufacturers decided to implement RL in their supply chain to benefit of this further advantage since they can attract a new customer segment.

The financial flows are affected by the volume of EOL products that could allow companies to reach economies of scale and by the EPR since the producers have to pay for the recovery of the EOL products.

Another important aspect that could affect the recycler's profitability is the quality of second hand materials: higher the purity of the recovered materials and higher the price at which it could be sold into the market.

According to the position in the supply chain, each actor involved has its own costs and benefits. For example, batteries manufacturers are involved in taking decisions for investments in product design in order to create products to be disassembled more easily (Dowlatshahi, 2000; Govindan et al., 2014). Moreover, they have to consider the product contingent liabilities as the costs associated with long term responsibilities for pollution and landfill waste.

2.6.8 F8 - Quality

This factor characterized the level of purity of recycled materials from EOL batteries. To operate the batteries must be characterized by high quality of the materials that make up them. In particular, the recovered materials in order to be reused for the production of new batteries need to have a level of purity above of a certain threshold, otherwise it can not be use in the production process of the same product but maybe it can be reused in other applications where the requirements are lower.

This factor is fundamental for the purpose of closing the loop (in the specific case: from a battery to a new battery) because if the purity doesn't respect the requirements, the recycled materials will be reuse for others applications. This factor is not so investigated in literature because authors are more focused on volume of EOL batteries and on volume of recycled materials.

Stock (1992) and Carter and Ellram (1998) state that recycled materials should be of the same quality as the corresponding virgin materials in order to be reused for the same applications.

In fact, low quality materials affect the overall quality of the products that consequently affects the company's sales and reputation (Dowlatshahi, 2000; Souza, 2013).

The contamination is the main problem when we deal with quality of recycled materials. In fact, purity of second hand materials is affected by both the recycling technologies and the materials components that made the product. In particular, when a product is made of a lot of components and each component is made by different materials, like the lithium-ion batteries, is hard to find a recycling technology able to separate all the material due to chemical and physical features of the product. In the case of heterogeneity of material, the recycler has no incentive to recover all the materials because after the recovery of some materials the recycling process could be very costly and therefore not sustainable for recyclers (Gaines, 2014; Rahman and Afroz, 2017).

Chapter 3
Research methodology

3.1 Research approach

In the last years, lithium-ion batteries system is characterized by a high degree of uncertainty. The expected increase in use of EVs has led to massive growth in the production of LIBs and this trend has only recently attracted the attention of academic communities. In fact, in the last years, based on the sustainable development goal of sustainable consumption and production, authors are dealing with several issues connected with this type of battery such as recycling technologies able to recover the valuable materials, availability of lithium and possibility to implement reverse supply chain activities for this type of product.

In the literature analyzed, the majority of authors use a qualitative research approach based on case study (Besiou and Van Wassenhove, 2015; Lau and Wang, 2009, Lapko et al., forthcoming; Knemeyer et al., 2002). As Yin (2009) said, the preference for qualitative research approaches is driven by the opportunity to examine and gain in-depth understanding of complex phenomenon. These approaches are preferred when "how" and "why" questions are being posed, when the investigator has little control over events and when the focus is on contemporary phenomenon within some real-life context.

Therefore, as done by Besiou and Van Wassenhove (2015), I decided to use a case-based research approach in order to obtain direct information from the main stakeholders involved in the battery industry (battery manufacturers, collectors and recyclers). This decision is driven by the features of the CLSC that is a complex system where multiple actors are involved in pursuing their own objectives.

3.2 Empirical setting

In order to achieve the aim of my work, I consider two automotive battery systems: the lithium-ion battery system and the lead-acid battery system. This last system is used as reference scenario, since it is a good example of circular supply chain. Lead-acid battery is a more mature product compared to LIBs and with a well structured market. In addition, it is the most recycled product with a rate of 99% and it represents a perfect reference of closed loop supply chain implementation.

The companies that are important to consider for both the lead-acid battery and the lithium-ions battery systems are battery manufacturers, logistics providers and recyclers. I decided to select these actors because they are the most important in the battery system and they cover all the relevant phases of the CLSC for a battery:

- ✓ the FSC with the battery manufacturer;
- ✓ the link between FSC and RSC with the logistics provider;
- ✓ the RSC with the recycler;
- ✓ the link between RSC and FSC (for the introduction of the recycled materials in the system) with the recycler.

In particular, actors involved in the LAB system, since the lead-acid battery is a mature technology, can give me a wide picture of the system and provide important considerations about the successful implementation of the CLSC for LABs.

For the lithium one, instead, I decided also to considered some car manufacturers because in the last years, based on the expected growth of EV, they are pushing a lot of efforts in the construction of electric battery plants.

In addition, some of the companies selected work both with lead-acid and lithium-ion battery and this allow me to better go deeper in insights of the two different types of technologies and make comparisons between findings of the two different system.

Furthermore, in my analysis, I considered also some associations which have the aim to control and coordinate the set of actors involved in the battery system. This allows me to gather additional information from actors that are not directly involved into the operations.

Since until now, in Europe a CLSC for LIB is not in place, I decided to focus my attention on the European boundaries, in particular focusing my attention on Italy.

All the companies selected are located within the EU, as geographical scope plays an important role due to different industrial infrastructure, different availability of materials, different technological competences and different environmental legislations.

3.3 Data collection

Based on the objective of my work, a qualitative research approach was followed.

The starting point that allowed be to have a deep understanding of the situation was the data collection phase, one of the most critical and important activities.

The sources of data collection were both primary and secondary data.

With primary data, I refer to interviews with company representatives and expert of the battery industry for allowing focused and accurate information gathering. From June 2017 to November 2017, I conducted individual interviews via phone, Skype or in person. The time of interviews ranges from 40 minutes to the longest of about 2 hours and with the permission of interviewees, I recorded the interviews

The contacted interviewees have different position titles since the division of responsibilities and organizational structure differ among companies. Therefore, for each company, according to the information needed, I decided to select the most indicated people to interview:

- ✓ For **batteries manufacturers**, I selected people working on the Operations which are directly responsible of the decisions taken in the productive processes (e.g. Operations managers). Moreover, I searched for people working on the Supply Division in order to acquire information about the relationship with others actors involved in the supply (e.g. suppliers of raw materials, competitors or companies involved in downstream activities). Another important division is the Research and Development unit that works on new product designs and improvements (e.g. Technical Manager). In the automotive sector, this unit is fundamental since it allows to introduce new innovations able to drastically changed the sector (e.g. Lithium-ion batteries). Finally, I consider also Sustainability Managers that are involved in taking decision based on regulations to pursuit the sustainable development.
- ✓ For **logistics providers**, I selected people working on the system as Manager in order to understand how the network is working and to acquire information about the features of the actors involved in the collection system, the ways of working of different actors, the flows of materials used and implications to follows.
- ✓ For **recyclers**, I selected people working on Operations which are directly responsible of the recycling activities (e.g Operation Manager) in order to have

information about the effectiveness of the technologies, problems and existing limitations. Other important actors are Sustainability Managers and people involved in the Research and Development unit interested in the definition of well performing technologies able to increase the efficiency of the recycling process (e.g. Technical Manager).

Moreover, in order to have a complete picture of the system, I contacted some experts of the sector as independent companies in charge of coordinating and controlling the overall system: EUROBAT and COBAT. I interviewed two Environmental engineers that cover the role of General Seretary of the two associations. These additional interviews were able to provide me a general perspective of the sector giving priorities to different aspects. The former, EUROBAT, is the Association of European Automotive and Industrial Battery Manufacturers. It was established with the aim to study all matters of interest to storage battery manufacturers and their subcontractors in Europe, Middle East and Africa.

The latter, CDCNPA (Centro di Coordinamento Nazionale Pile e Accumulatori), works in Italy; it was defined by the Italian Legislative Decree 188/2008 and it has the task of coordinating the activities of its associates in order to make consistent and uniform procedures for collection throughout the national territory.

To collect information, a semi-structured interview protocol was employed at all interviewees in order to ensure that all the key topics would be addressed (the list of questions made during the interviews is provided in the Appendix 1).

This way of collection of data allowed me to gain additional information specific to each company. The main topics covered during the interviews are the following:

- ✓ Engagement of a company (manufacturer, logistic providers, recycler) in CLSC for automotive batteries over the years in terms of both forward and reverse SC (product design, manufacturing processes, involvement in the management and collection of EOL batteries, commitment in performing recycling activities, remarketing of recycled materials)
- ✓ Factors influencing implementation of CLSC via recycling for automotive batteries in a temporal perspective, past and current enabling and bottleneck conditions.
- ✓ Company’s perspective towards changes in the batteries system (e.g. market dynamics, policy dynamics) which affect company’s business decisions

During the data collection, I also collect secondary data (collection from March 2017 to November 2017) in order to gather further information. The list of key topics described above, has been also used for search for secondary data.

I reviewed Industrial and Scientific papers in order to collect information about technology development and reviews, and about network structures of collection systems. This is necessary to better understand which is the actual situation and which are the main fields of research. In particular, I focused my attention on the understanding of recent developments in terms of lithium recycling technologies since so far, an economic and environmental sustainable technology is missing.

A structured keyword search was conducted on major publisher websites and databases (Google Scholar, Elsevier ScienceDirect, ResearchGate GmbH, Scopus). Therefore, the following keywords were used: "battery recycling technologies", "battery recovery", "battery recycling infrastructures", "battery recycling", "opportunities for battery recycling" with the focus on lead-acid and lithium-ion batteries and the papers selected are published on the "International journal of energy technology and policy", the "International journal of sustainable resource management and environmental efficiency" and the "Journal of industrial engineering and management".

In the table below (table 6) there is the list of companies selected according to their different supply chain position with details about the sources of information collected.

Table 6: List of companies considered. (S=SMALL; M=MEDIUM; L=LARGE).

Company	**Company Size**	**SC Position**	**Italy/EU**	**Interviewees Position**	**Secondary Data**
M1	S	LAB Manufacturer	Italy	- Operations Manager	- Company Website
M2	S	LIB Manufacturer	Italy	- Technical Manager	- Company Website
M3	M	LIB Manufacturer	EU	- Supply Chain Manager	- Company Website - Sustainability Reports
M4	M	LAB/LIB Manufacturer	Italy	- Operations Manager	- Company Website

Company	Company Size	SC Position	Italy/EU	Interviewees Position	Secondary Data
M5	M	LAB/LIB Manufacturer	Italy	- R&D Manager	- Company Website
M6: PSA GROUP	L	Car Manufacturer	EU		- Corporate Social Responsibility Reports - Annual Reports - Sustainability Reports - Company Website
M8: DAIMLER	L	Car Manufacturer	EU		- Company Website - Annual Reports - Corporate Presentation - Sustainability Reports
C1	M	Collector (also recycling)	Italy	- R&D Manager - Operations Manager	- Company Website - Annual Reports
C2	M	Collector	Italy	- Business Development Manager	- Company Website
C3	M	Collector	EU	- Technical/Audit Manager - Technical Regulation Manager	- Report 2016 - Company Website
R1: ACCUREC	L	LIB Recycler	EU		- Company Website
R2	M	LIB Recycler	EU	- Technical Manager	- Company Website
R3	M	LAB Recycler	Italy	- Technical and Production Manager	- Company Website - Model of Organization

Company	Company Size	SC Position	Italy/EU	Interviewees Position	Secondary Data
R4	M	LAB Recycler	Italy		- Company Website - Corporate Social Responsibility Report
R5	M	LAB Recycler	EU	R&D and Process Manager	- Company Website
R6: RECUPYL	M	LIB Recycler	EU		- Company Website
R7: UMICORE	L	LAB/LIB Recycler	EU		- Company Website - Annual Reports - Technical presentation - Strategic Overview [Horizon 2020]

Moreover, I also analyzed information from corporate website and reports or papers published by each company as Annual Reports, Corporate Social Responsibility Reports and Sustainability Reports in order to ensure data triangulation (Eisenhardt, 1989). These documents allowed me to deeply understand the activities performed by each company with the possibility to gather more information about its way of working and maybe because some topics did not come out during the interviews.

In particular, for car manufacturers I deal only with secondary data according to my decision to focus the attention especially on the "traditional" players and I consider quite recent documents since the involvement of car manufacturers in the LIB system is a recent phenomenon. This additional collection of data allows me to overcome the limitations of possible interviewee bias and interviewer bias.

Therefore, I coded indications for factors in all the data collected (both primary and secondary) for both the battery systems and I tried to define implications of each factor. For example, for the lead-acid battery system the battery manufacturer M1, when he explained me the design of a lead-acid battery, used these words: "a lead-acid battery is a simple product and it's composed by only 4 components which are very simple and standardize and therefore the recycling activity for this type of product is not a problem". From this statement, I came up with the result that the standardization of the LAB and its simple design facilitate disassemble and further recycling. Another manufacturer (M4) reported this "from 2006, battery producers are obliged to take care about EOL products". In this case two factors must be considered: the first is the legislation (F3) and the second the organizational set up (F4), since companies are responsible to take care of the recovery of this type of product. Based on the lithium-ions battery system, instead, all interviewees referred to the growing uncertainty about EV diffusion. A manufacturer (M3) told me "nowadays we can not say that there will be enough virgin lithium to feed all the companies that are producing LIBs" and therefore I refer this statements with the production volume of a company and therefore its financial stability (F7) but also the importance of volume of EOL lithium-ion batteries as a new source of supply (F2). R2 explained me how it is difficult to perform recycling activities with LIB. It argued that this battery is a complex product since it is composed by a variety of materials. Moreover, in the market there are different designs. Therefore, based on his sentences the technological aspects (F1) of product design and recycling activities are classified as critical. C1 told me about the projects that it is doing with CNR. In this case the companies interactions (F6) play an important role in defining new solution to solve the criticalities related to the management of EOL LIBs.

3.4 Data analysis

Ended the data collection activity and the codification process, I analyzed each factor according to different perspectives. I used the same process to analyzed the two battery systems.

The generic process followed consists of three steps:

- ✓ At the beginning, I analyzed each factor within each company in order to investigate how each factor affects the way of working of each company following a closed loop perspective; I defined for each factor pro and cons.
- ✓ Then, I analyzed each factor within each supply chain position in order to examine the behaviors of the different players in pursuing the CLSC. Maybe a factor that is considered a bottleneck for manufacturers, by the recyclers is seen as an enabler.
- ✓ Finally, I analyzed each factor throughout time This allows me to define possible milestones over the years that affect the implementation of the closed loop supply chain for the specific battery system. For example, since the LAB is a mature technology compare to the LIB, from an analysis throughout time it is possible to discover important events that affected the development of the LAB CLSC. Maybe, these events could be replicated for the success of the LIB CLSC.

At the end of the analysis of the two systems under investigation, I performed a comparative analysis between the lead and the lithium battery systems in order to describe how the two different systems are different and what are similarities. Then, based on the good example of LAB CLSC (as lessons learned), in Chapter 7 I proposed a framework in which there are the required actions in order to develop a successful CLSC for LIBs.

Chapter 4
Lead-acid Battery Analysis

4.1 Lead-acid battery description

Lead-acid batteries are the world's most recycled consumer product. The success of this system is proven by a study (The Availability of Automotive Lead-based Batteries for Recycling in the EU) performed by EUROBAT between 2010 and 2012. The research establishes that the collection and recycling rate of automotive lead-acid batteries over the period 2010/2012 was equal to 99%. Over the total amount of automotive batteries available for collection (1,110,730 tons), the total amount of automotive battery collected was 1,093,645 tons in the two years under investigation. Therefore, according to the research conducted by EUROBAT, more than 99% of all lead-acid batteries are recycled compared to the 68%[6] of aluminum soft drink and beer cans, the 72 %[7] of paper and the 70%[8] of glass bottles.

The 80% of a typical lead-acid battery is composed by materials that are recycled from oldest batteries (EUROBAT, 2015). In fact, the battery's production, distribution and recovery cycle follows a virtually "closed-loop". The EOL lead-acid batteries, instead of being dumped in landfills, are collected by authorized actors and they are sent to recycling centers where the recovery activities are performed under strict environmental regulations. From 2006, such activities are regulated by the EU Battery Directive (2006/66/CE) that promotes a high level of collection and recycling of waste batteries and a better environmental performance of all operators involved in the life cycle of batteries.

[6] European Aluminium Association 2013

[7] Confederation of European Paper Industries 2013

[8] European Container Glass Federation 2014

A lead-acid battery is a very simple technology and it is made of four main components: a positive plate (cathode), a negative plate (anode), a separator that keeps distant the two plates in order to avoid short circuit and an electrolyte solution. All these components are contained in a plastic made box (Figure 8).

Since its invention in 1859 by a French physicist Gaston Planté, the lead acid batteries have attracted a great deal of attention because of its ability to supply higher current densities and lower material (lead and sulphuric acid) and maintenance costs. This typology of battery is the oldest of rechargeable battery and it is the most used all over the world.

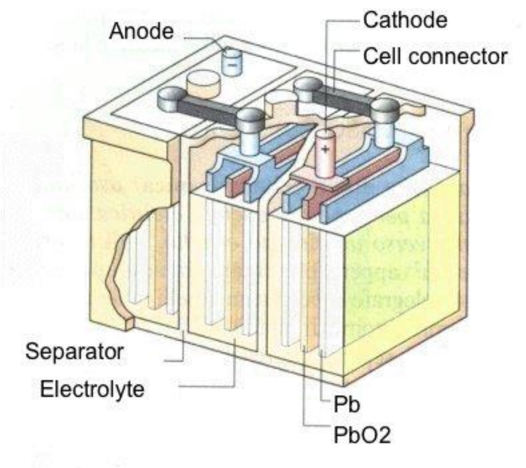


Figure 8:Main components of a Lead-acid battery

In table 7, the main components of a LAB are presented.

Table 7:Description of the main components of a LAB
(PE = polyethylene; PVC= polyvinyl chloride; PP = polypropylene)

Cell component	Material	Description
Cathode/Cathode plate	PbO_2/Pb	Positive plate
Anode/Anode plate	Pb	Negative plate
Electrolyte	H_2SO_4	Electrolyte dilute H_2SO_4 solution where the two plates are submerged and there is the ions passage
Separator	PE or PVC	Important component that keeps distant the two plates in order to avoid short circuit
Cell case	PP	Container that contains all of the above mentioned components

4.2 Analysis of the lead-acid battery system

The table below, based on interviews and secondary data, presents the evidence of factors affecting CLSC for lead-acid battery. In order to assign the relevance that each factor has for the different supply chain actor, I use "xx" for factors that have huge relevance and "x" for factors with lower relevance. Finally, the empty parts refer to factors that are considered not relevant and that they are not mentioned during interviews.

Table 8: Evidence of factors according to the LAB actors interviewed ("xx" high relevance, "x" relevance).

Factors / Companies	**F1** Technological Aspects	**F2** Volume	**F3** Legislation	**F4** Organizational Set Up	**F5** Infrastructure	**F6** Companies Interactions	**F7** Financial Aspects	**F8** Quality
M1	x		xx	xx	x		x	x
M4	x		xx	xx			x	xx
M5	x	x	x	xx		x	xx	
C1		xx	x	x	xx	xx	x	
C2			x	xx	x	x	x	
C3		x	x	x	x	x		
R3	xx	xx	x		x	xx	xx	x
R4	x	x	x			x	x	x
R5	xx	xx	x	x	x	x	xx	x
R7	x	x	x			x	xx	xx

4.2.1 LABs: evidence of each factor

Taking into consideration the factor referring to the *Technological Aspects* (F1), all manufacturers (M1, M4, M5) agree on the definition of the automotive LAB as a simple product characterized by a standard design. In fact, the lead-acid battery is made by few components and few materials (Pb, H_2SO_4, PE, PP). Moreover, no chemical issues affect the disassembly of the battery allowing the performing of easily recovery activities. The product standardization and simplicity of components are defined as key enablers for the pursuing of the closed loop perspective. M1 underlines how these factors allow lead-acid battery manufacturers to better fulfil their EPR (F4). In fact, M1 mentions the following: “Recyclers, when they perform the recovery of materials form this type of product, do not require specific and particular technologies. They smelt the components made of lead and then, in order to define high purity materials, they refine them”.

Moreover, since all the manufacturers use the same raw materials: lead, lead oxide and sulphuric acid and the battery design is similar for all producers, an automated technology can be used for battery disassembly (M4 and R3).

Since the simplicity of the process, manufacturers have only to pay a fee (F7) to collectors and to recyclers in order to fulfil their responsibilities (F4) for taking back their used products at the end of the useful life.

R5 and R7 describe the recycling process similar to the description provided by M1. The recycling technology is not a source of problems for the implementation of a CLSC. It is simple and standardized.

Among the variety of technologies used, R3 explained that the thermal process it is the most diffused among Italian recycling companies. The main reasons are the simplicity of the activities and the valuable outputs achievable through the process. The recyclers, in order to perform their activities, need only a big furnace. The process consists of three subsequent phases: crushing, smelting and refining (see Figure 9).

- ✓ **Crushing**: the batteries are broken and the components such as the lead metal, paste, plastics and electrolyte acid are separated.

Then, the metallic components of a batteries follow a recovery process composed by two phases:

- ✓ **Smelting**: the lead embedded in the battery is collected smelt into furnaces
- ✓ **Refining**: in order to eliminate impurities from the smelted lead. In this way, the output of the process is recycled lead that it is characterized by the same level of quality of virgin lead. Therefore, it can be reuse for the production of new batteries or to make other leaded products such as those employed in building construction and others applications.

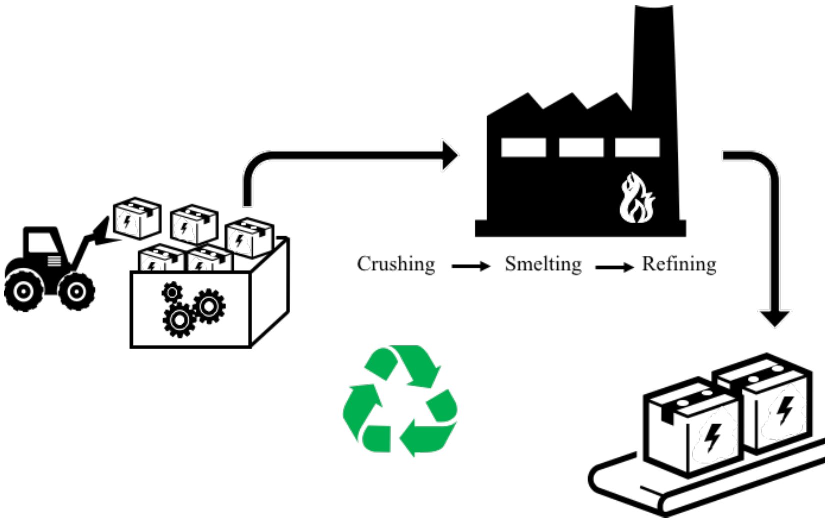


Figure 9: LAB recycling process

The output of the process is a valuable lead, which has the same features of the virgin lead (F8) (M4). Thanks to the simple product design and the presence of few components with low materials embedded, no problems of contamination (F8) and chemical issues arise during the recycling process (R4). An additional advantage highlighted by R3 is that LAB manufacturers use the same design and therefore, there is no need to perform sorting activities or to define dedicated processes for the different types of batteries.

Although the recycling process allows the implementation of a successful CLSC for EOL LAB, R4 mentioned an issue that is not linked directly with the CLSC perspective but that follows the primary aim of sustainable development. He highlights that in the market, since the product has always remained the same and high quality of recovered materials is easily ensured, there are companies that have quite old plants and outdated technologies. These old technologies are characterized by high level of energy consumption and pollution.

Following this environmental issue, in these years different researchers are focused in defining new technologies able to manage EOL batteries in a greener way. For example, Zhang et al. (2016) focus their attention of two new sustainable and environmental friendly processes: paste-to-paste recycling and hydrogen-lead oxide fuel cell method. These processes allow recycling EOL lead-acid batteries in a more efficient way and with lower energy consumption.

In the last years, there has been growing pressure to achieve sustainable greener recycling methods to solve the problem of environmental pollution caused by emissions of lead particulates and sulphur oxides in the traditional smelting route. This secondary pollution must be handled and reduced in order to increase the overall benefits achievable with the performing of recycling activities.

Volume (F2) is one of the most important factors for recyclers. R3 and R5 consider this factor fundamental for a proper implementation of CLSC. In fact, a remarkable volume of EOL batteries is needed to ensure the reaching of sufficient capacity of the recycling process. A stable and constant flow of EOL batteries is required to feed the process and achieve economies of scale. In fact, higher the volume of EOL batteries and higher both the economic advantages in terms of company profitability (F7) and the operational efficiency (R4).

The same reasoning is expressed by C1. In fact, large amounts of EOL batteries to collect permit collectors to exploit benefits resulting from activities in big scale (C1, C3).

Recyclers and manufacturers agree in defining regulations (F3) as one of the main factors that ensures high volume availability of EOL batteries. In fact, the Battery Directive (F3) obliges manufacturers to take care about spent batteries according to the EPR (F4). For this reason, recyclers (R4, R5) are confident of future flows of spent automotive batteries. Moreover, in the last century, the sales of lead-acid battery reached a state of technology maturity (F1), the amount of wasted batteries has increased overtime and therefore and high potential input for recycling activities is expected in the following years. In addition, although the increasing trend of automotive LIBs sold, automotive lead-based batteries will dominate the market for many years (M5). The main reason is the lower price of LABs that keeps market appetite for this type of battery (M5).

In Figure 10 we can see how the volume of LAB is grown over the years (Davidson et al., 2016).

However, there are also uncertainties about the future flows of EOL LABs. R7 referred to uncertainty of the product life cycle in terms of both time and volume. Time is affected by the life cycle of the product (5/6 years) and by the different types of product return: the product could return as damaged, or maybe because it reaches its end of life. Volume, instead, is affected by different aspects. CDCNPA highlighted that volume is primarily affected by the collection system (F5). The infrastructure should be developed in order to be able to collect as much products as possible. Therefore, although a high collection rate is registered in these years, further improvements can be done in order to recycle the highest number of batteries allowing both collectors and recyclers to exploit economies of scale (F7). The second aspect that affects volume of

EOL lead-based batteries is the presence of illegal flows, in which batteries are managed in wrong ways (C1). Finally, volume is also affected by secondary use: EOL LABs can be used for storing energy from renewables (M5 and C3).

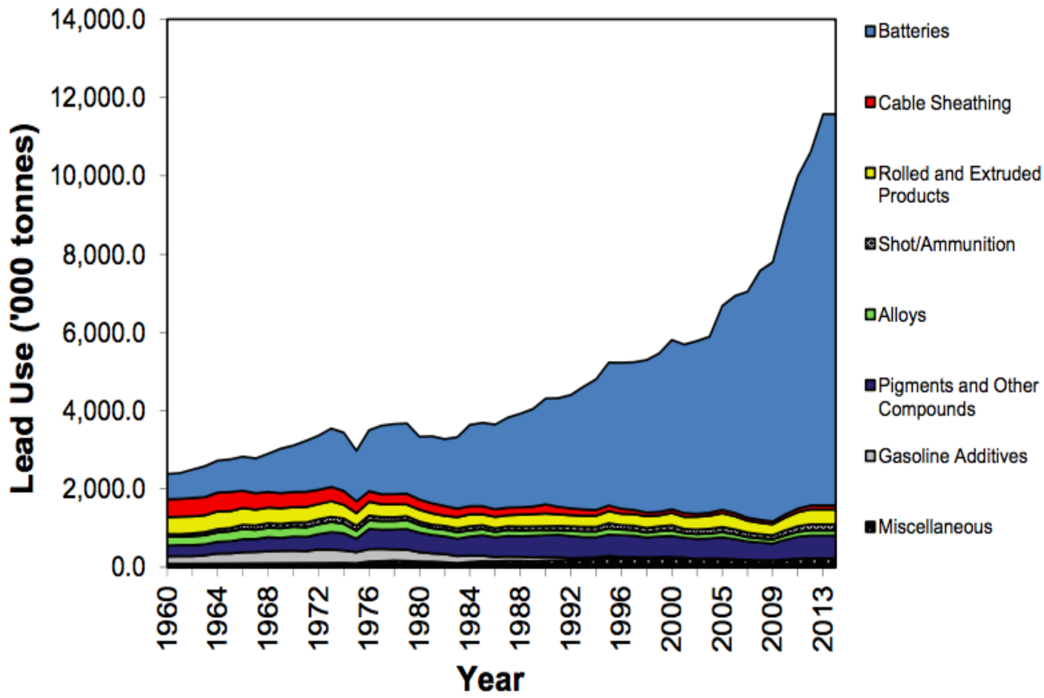


Figure 10: Global applications of lead from 1960 to 2014 (Davidson et al., 2016).

CDCNPA stated that in 2016, in Italy, more or less 230.000 tons of batteries were treated. Considering that in the same years there were marketed 300.000 tons of new batteries, the 80% of batteries were recycled. The remaining part refers to batteries that are used as storage of renewable energy sources or are managed in a wrong way (illegal flow). This last option, in 2016, accounts more than the 10% of EOL batteries (CDCNPA). This illegal market is composed by actors that take advantages by performing incorrect actions. In fact, "illegal recyclers" do not follow legislations that obliged companies to perform under strictly conditions and therefore, they faced less bureaucracy costs (F7). One of the most important among the treatment costs is the cost related to the disposal of the acid contained in the battery. The electrolyte solution is toxic for the environment and for humans and therefore, in Italy, as in other countries, there are rigid rules to follow for the proper implementation of a correct disposal. Despite this, there are some foreign countries were there are less restrictive rules where recyclers perform their recycling activities in order to gain more benefits.

If now we shift the attention on the output of the recycling process, R5 states that all the recovered lead from batteries is reused for the production of new LABs. This is the consequent result of the successful implementation of LABs CLSC and the presence of a robust market demand for recycled lead. Batteries manufacturers and recyclers (M5, R3, R5) share in defining recycled lead as an enabler of the closed loop perspective. It ensures benefits for both the players involved in the supply chain.

For manufacturers, the recycled lead can be used as input for the production of new batteries because it has the same technical features (purity, F8) of virgin lead and lower market price (F7) compared with the virgin one.

Legislation (F3) is the only factor cited by all the interviews and by the majority of secondary data analyzed. The factor forces producers to take-back their waste products from customers and to recover them. In fact, all the directives have the philosophy of extended producer responsibility (EPR, F4) at their core:

- ✓ the Directive on End-of-Life Vehicles of September 2000 (2000/53/EC);
- ✓ the Directive on Waste Electrical and Electronic Equipment (WEEE) on January 2003 (2002/96/EC) and on July 2012 (2012/19/EU);
- ✓ the Directive on Batteries on September 2006 (2006/66/EC).

In particular, the Batteries Directive (2006/66/EC) adopted in 2006, is defined by collectors as a key milestone in the definition of the battery system as we know. It intends to contribute to the protection, preservation and improvement of the quality of the environment by minimizing the negative impacts of batteries and waste batteries. To achieve these objectives, the Directive prohibits the marketing of batteries containing hazardous substances like mercury and cadmium, and defines measures to establish schemes aiming at high level of collection and recycling as one of the enabling elements for closing the loop. C1 highlights that in the directive there are no specific targets to fulfil for automotive batteries. Indeed, the European Commission, with the introduction of the EPR (F4), combined with the ban on landfilling and incineration, considers enough to ensure that batteries are collected. Moreover, the use of financial incentives (F7) and the application of penalties for infringements aim to ensure that batteries are collected properly. As a result, nearly 100% of EOL automotive batteries are already being collected. In particular, the only target set for LABs is for recyclers, who have to recover at least the 65% of the battery mass.

In order to reach this target, in the Directive there are listed all the activities that companies can and can not perform in terms of collection, treatment and recycling, disposal and exports.

In Italy, the Directive was transposed through the Legislative Decree 188/88, which sets the boundaries of the allowed activities.

Based on these considerations, batteries manufacturers (M1, M4 and M5) are obliged to deal with the take-back of their batteries placed on the market and they see the EPR as a mandatory obligation to fulfill.

For collectors and recyclers, instead, in the Battery Directive (2006) and in the further integrations there are set targets of collection and recycling rates to fulfill.

Recyclers (R3, R4, R5 and R7) do not see legislations as a limit because they are able to reach the targets in an easily way since there are no criticalities related to the recycling process and because the collection system is well performing, ensuring a remarkable quantity of EOL batteries to manage. Moreover, R3 highlights that it started to perform recycling activities before the introduction of the Directive since the recycling activities were seen as a source of value creation allowing the company to make profit (F7). R3 adds that the benefit of the introduction of the Battery Directive was in terms of EOL volumes, since after 2006 the majority of EOL LAB are recycled.

In addition, collectors, according to the different solutions of collection implemented, see legislation as a driver for the proper implementation of a battery closed loop supply chain. C3 explained how these legislations are important for rising awareness on battery manufacturers about the products that they sell into the market.

Moreover, in Italy, legislations are considered the enabling factor that allow the implementation of a successful collection system. In 1988, through the D.Lgs. 22/97, it was established the first Mandatory Consortium. Then, with the Battery Directive and the liberalization of the market enshrined in Legislative Decree 188/08, different collection and recycling systems appeared. These actors represent the working environment of today.

Organizational Set Up (F4), as mentioned in F3, is an enabling condition in pursuing the battery CLSC. The table 8 shows that the factor involves more battery manufacturers and collectors.

In fact, with the introduction of the EPR (Batteries Directive, 2006/66/EC) the involvement of the battery manufacturers in the product life cycle is changed.

M4 and M5 highlighted that traditionally, manufacturers have seen the remit of their responsibility ending at the termination of the product's warranty period, with ownership (and ultimately accountability) of the product being passed to consumers. However, the introduction of EPR aims to change this, necessitating a rethink of the traditional battery life cycle to encompass more end-of-life considerations. This was done in the hope of promoting more sustainable closed-loop recovery and recycling.

In fact, with the escalation in environmental regulations (F3) comes an increase in costs associated with the collection, treatment and processing of the end-of-life products and a lack of distinction about which stakeholder should be responsible for covering these additional burdens.

Therefore, EPR is an important instrument adopted to hold manufacturers responsible for managing their products at end-of-life dealing with the growing volume of battery waste (C2).

In Europe, there are three different typologies of systems, which try to answer to the fulfilment of the EPR (CDCNPA):

1. **Taxation system**, where producers finance costs through taxes or fees (which in some cases feed a fund) but the organizational and operational responsibility of the collection falls on a state-controlled body (Slovakia, Lithuania, Malta, Iceland, Denmark).
2. **Compulsory consortium system**, where the whole industry of manufactures and imports accumulators meet in a single organization that is funded by the participants and it carries out the collection activities on their behalf (Belgium, Greece, Cyprus, Luxemburg, Netherlands).
3. **Competitive collection system**, (C1, C2 and C3), where manufacturers can create or choose different organizations that collect waste batteries against the payment of a fee, which may also vary between one organization and another (Italy, France, Germany, Slovenia, Estonia and others). Moreover, in many countries, as in Italy, there is an entity that controls and coordinates the system as a whole (in Italy CDCNPA).

Focusing on the *competitive collection system*, the manufacturer's responsibility can be handled or in an individual way, when a producer directly realizes a collection system on a national scale for the conferral of exhausted batteries, or in a collective way. This last option consists of consortia such as C1, C2 and C3, which collect batteries for different manufacturers. In this case, each producer has to pay a fee, based on the volume of battery that the PRO, the Producer Responsibility Organization, has to manage.

In the Italian scenario, M1, M4 and M5 as the majority of manufacturers do not perform individually the recycling activities. They contract with third parties (e.g. collection companies or recyclers) who handle the wastes. The main reason highlighted by C2 is that due to the presence of economical (F7), governmental (F3) and environmental considerations, battery manufacturers are forced to build-up with third parties efficient and effective spent battery systems for collection and recovery activities. In particular, M1 is able to collect its EOL LABs and then it sends them to recycling. M1 explains me that it has a collaboration with a unique recycler in Italy, who is able to manage all the volume of its EOL batteries. M4 and M5 instead pay a collector for the collection of their EOL batteries. The collector is also in charge of the recycling activities.

The *Infrastructure* (F5) is defined by CDCNPA and C1 as the means through which it is possible to perform the recovery activities and to implement a CLSC. In fact, EOL LAB can reach the recycling facilities thanks to the well-structured infrastructure that links all the battery manufacturers with the respective recyclers (C2). C1 states that the success of the network is due to the high capacity that both collectors and recyclers are able to manage.

In EU, used automotive lead-based batteries are typically returned to the point of sale such as vehicle workshops, vehicle dealerships and accessory shops, or they are returned to recycling businesses or metal dealerships. In all cases, then, they are sent to collection points. Finally, the batteries are picked up at collection points by specialized companies, who transport and deliver the batteries to secondary smelting plants (C3).

The collectors interviewed are companies that perform all the logistics activities able to fulfill the requirements that manufacturers have to accomplish (F4). They are in charge of managing a system able to perform collection, transport, storage, sorting and treatment activities. C1, in order to boost competition among collectors (F6), decided to provide also recycling activities. The decision was driven by the possibility to provide a more reliable and qualitative service.

Indeed, each collector, based on the activities that performs, has its own collection network and infrastructure. C2 underlined that for collectors the accomplishment of the manufacturer’s EPR (F4) is only a matter of business. Their scope is to serve customers (manufacturers) offering a service that allows the manufacturers to meet their EPR duties. Therefore, C2 explained that in order to reach economies of scale (F7) and exploit in an efficient way its own infrastructure, they offer collection activities for a variety of products: portable and automotive batteries, accumulators, WEEE and photovoltaic panels. The same is performed by C1 that offers businesses integrated and personalized services of collection, treatment and recovery services for spent batteries and accumulators, WEEE, photovoltaic modules and used tires, in compliance with the highest environmental sustainability standard.

In the Italian scenario, Cobat (C1) is the perfect example of a well-structured infrastructure able to guarantee a range of services from the highest quality standards throughout the country. The logistic network consists of 70 companies in possession of the authorization requirements, which represent the operational arm of the Consortium (Figure 11). Each company belonging to the consortium is able to meet the needs of each battery manufacturer according to a proximity logistics. This allows also to reduce emissions into the atmosphere and to transfer costs. The consortium works following the key features of a close loop system and the sustainability issues.

Finally, R3 highlights that the infrastructure is not a problem for LAB CLSC because the existing players, who perform collection activities, through the exploitation of their infrastructures, are able to collect huge amount (F2) of EOL batteries able to feed the recycling processes.

Figure 11: Geographical distribution of the 70 companies belonging to the consortium (Cobat, 2016).

In addition, R5 reported an issue that is affecting the infrastructure: the collection of EOL LIBs along with LABs is causing trouble at secondary lead smelters. In fact, many current LIBs are indistinguishable from lead-acid batteries on purpose since they are used as substitutes for SLI (starting, lighting and ignition), vehicles, motorcycles and other applications (ILA, 2014). This inclusion of LIBs in the input stream of secondary lead smelters has resulted in fires and explosions. Obviously, such facts pose a serious danger and must be prevented. In these years, EUROBAT is working in order to find solutions to this problem of cross-contamination of battery types in recycling streams (EUROBAT, 2014).

Moreover, this factor is directly linked with F6 because the sharing on the infrastructure affects the different actors involved in the SC in two different ways: direct and indirect.

The collectors are directly affected because through the sharing of the infrastructure among different battery manufacturers, they can exploit different advantages such as economic and operational efficiency advantages (C1 and C2). C3 explained that is able to achieve economic advantages thanks to the exploitation of economies of scale. In fact, the possibility to offer collection services to a variety of battery manufacturers allows the collector to use in an effective and efficient way the infrastructure without losing money and efforts.

Also recyclers are affected in a direct way because the remarkable volumes that comes from the collection system allows to exploit economies of scale at the plant level (R3 and R4). But as mentioned for F5, R5 reported a problem that is occurring after the diffusion of automotive LIB into the market. Some collectors by the simultaneously managing of LIB and LAB are more oriented to achieve economic advantages instead of paying attention to separate the two different technologies. In fact, recently, Li-ion batteries have wound up in lead-acid battery recycling plants, causing explosions. Therefore, R5 stated that coordination and transparency must be between battery manufacturers and collectors in order to prevent these accidents.

The sharing of the infrastructure affects also indirectly manufacturers. In fact, battery manufacturers since the same collector serve them, they can decide to cooperate in order to achieve economic benefits through the sharing, for example, of a warehouse where store the EOL LABs which must be collected by the same logistics provided.

A factor that is seen in different ways by the different companies is the *Companies Interactions* (F6) factor. M5 particularly emphasized the possibility that manufacturers and collectors can exchange information (e.g. batteries sold into the market, battery collected in predefined time windows etc.); this information sharing allows boosting the visibility of battery flows.

Also R3 and M5 stated that the sharing of information (e.g. battery chemist, materials embedded in the battery etc.) is fundamental for the success of closing the loop. As mentioned in F1, the battery product design and the recycling technology are linked each other. Therefore, in order to easily perform recycling activities and improve recycling rate, battery manufacturers and recyclers should cooperate in order to improve the battery design for recycling and to enhance the deployment of recycling methodologies.

R4 mentioned also the presence of competition between recyclers because since the lead-based battery recycling is a source of profit (F7) each company would manage more volume as possible according to its own maximum recycling plant capacity (F1). In fact, higher competition means lower volume to manage for each recycler and therefore lower profit. Moreover, R7 highlighted the existence of another type of competition. In the last years, since recycled lead became the first source of lead, competition was created between lead-acid battery recyclers and lead mining companies.

The main reasons are two:

- ✓ Recycled lead ha the same quality (F8) of the virgin lead;
- ✓ The price of recycled lead (F7) is lower than the price of virgin lead.

Another fundamental factor for the success of the closed loop perspective is the *Financial Aspects* (F7), which analyses the economic feasibility of the overall system.

C2, R3 and R5 directly link the financial dimension with the price of lead. In fact, recyclers perform the recovery activities only when the market price of lead is able to recover the cost supported for the recycling of EOL lead-based batteries. R3 highlights that the price of lead drives all the system. If the price is higher enough to cover the recycling costs, no problems arise from the recycling process. Otherwise, when the price is lower than the costs, incentives are needed.

Therefore, the economics of lead-based battery recycling is sensitive to the lead market price, which is characterized by volatility and it can fluctuate from year to year (as shown in Figure 12). M5 supports that possible temporary stocking of batteries could affect the yearly figure for batteries collected. This involves smelters temporarily storing lead-based batteries to ensure that they obtain the best possible price for their recycled lead.

Despite the behavior adopted by recyclers, M4 and M5 indicate that, due to the high cost of virgin lead, it is more convenient for lead-based batteries manufacturers to use recycled lead instead of the mined one. In addition, no problems of lower quality (F8) are associated with the recycled lead and thus the only variable to take into account is the market price, argues M1. Moreover, this new source of materials, it ensures stability and security of the procurement phase of the supply chain.

For recyclers, selling the recycled lead is a way to make money (F7) that ensures the feasibility of their business model. LAB is a wide diffuse product in the market and it will remain in for many years. Therefore, future financial flows are ensured since battery manufacturers prefer the recycled materials compared to the virgin one.

In addition, the introduction of this new source of supply has effects on the mining industry (F6) since less raw material needs to be extracted. This allows to reach lower energy consumption and lower levels of pollutions. R7 states that "Securing adequate volumes of raw materials is an essential factor in the ongoing viability of our product and service offering" (Umicore, Annual Report 2016).

Figure 12: Lead market price (LME).

Although the market is characterized by uncertainty due to the price fluctuation, all the recyclers agree on the definition of this market as a "market with value". In fact, C3 supports that lead batteries recyclers are able to gain form each battery the 40% of its market value. C1 adds that the recyclers' break-even price is approximately equal to 1000 € for each ton of lead. With the actual level of price of lead (about 2000 €/ton) recyclers are able to gain a lot of money. In addition, if the volume of batteries recovered is remarkable (F2), they gain the additional benefits related to the exploitation of economies of scale. Thus, the LABs recycling is considered a very profitable activity.

For the success of the CLSC not only the price of the recovered material is important but also its *Quality* (F8) plays a relevant role (M5). In fact, LAB manufacturers for the production of lead-based batteries need to use high quality materials, explains M1. The high quality is defined in terms of purity of materials: lower the material contamination and higher the value.

Since the recycling technologies (F1) are able to recover lead with a purity level of 99,97%, R4 and R5 are confident in saying that the recycled lead has the same features of the virgin lead. R3 adds that this result is allowed by the simplicity of the lead battery: a simple product made of few components and few materials (F1).

M4, according to the positions of recyclers, says that lead-acid battery manufacturers are encouraged to buy secondary lead not only for its low price compared to the virgin one (as already explained), but also for its high quality standard.

This involves that the flow of recovered lead is easily placed on the market by securing the closure of the loop.

4.2.2 LABs: evidence of factors for the different SC positions

Based on each supply chain position, in the table below (Table 9) are presented the degrees of importance of each single factor for closing the loop of LABs.

I defined three different categories. Each category is associated with a color:

- ✓ **Green**: huge importance for the SC position;
- ✓ **Yellow**: relevant for the SC position;
- ✓ **White**: no evidence.

Table 9: Evidence of factors for the different SC positions.

Factors / Company	F1 Technological Aspects	F2 Volume	F3 Legislation	F4 Organizational Set Up	F5 Infrastructure	F6 Companies Interactions	F7 Financial Aspects	F8 Quality
M1	x		xx	xx	x		x	x
M4	x		xx	xx			x	xx
M5	x	x	x	xx		x	xx	
C1		xx	x	x	xx	xx	x	
C2			x	xx	x	x	x	
C3		x	x	x	x	x		
R3	xx	xx	x		x	xx	xx	x
R4	x	x	x			x	x	x
R5	xx	xx	x	x	x	x	xx	x
R7	x	x	x			x	xx	xx

Based on the battery manufacturer perspective, the most relevant factors are *Legislation* (F3) and *Organizational Set Up* (F4), which represent the drivers that force them to perform additional activities for the recovery of their EOL products. They have to fulfil these obligations otherwise, if they fail to comply with them, they have to face costly sanctions.

The other two important factors are *Financial Aspects* (F7) and *Technological Aspects* (F1). The former (F7), following the aim of closing the loop, is affected in two opposite ways:

- ✓ Cash outflow: the manufacturer has to pay a fee to the collectors in order to finance the collection system (- €);
- ✓ Saving of money: the manufacturer can save money by buying recycled lead at a lower price than the virgin one.

Therefore, even though battery manufacturers see the fee payment negatively, the same, by funding the system that allows the CLSC, can gain cost advantages.

The latter factor (F1), the technological one, is important because it is considered a facilitator of closing the loop. The manufacturers argued that thanks the simple and standard battery design the performing of recycling activities is not a problem and therefore, they can fulfil easily their product responsibility.

Based on collectors, since their role in the CLSC is the fulfilment of the battery manufacturer responsibility making EOL LABs available for recovery activities, the most relevant factors are those related to the functioning of network system and to the definition of different relationships among companies.

Indeed*, Organizational Set Up* (F4) and *Infrastructure* (F5) are fundamental for the proper implementation of the CLSC. Through the implementation of collective schemes and the right definition of the infrastructure, which is able to guarantee a high collection rate, collectors can meet the battery manufacturers' responsibilities and they can make large amount of EOL LABs available for recyclers.

Moreover, the *Companies Interactions* factor (F6) is fundamental for collectors.

In fact, different issues can be considered:

- ✓ Sharing of information with battery manufacturers: this allows to efficiently organize the collecting activity because it boosts the visibility of collectors on possible future flows of EOL batteries (e.g. number of lead-acid batteries sold into the market in a particular time window, forecast of EOL LABs, number of returned batteries);
- ✓ Sharing of the infrastructure among battery manufacturers: this allows collectors to reach economic advantages in terms of economies of scale. In fact, for example, the collector can use the same truck to collect lead-acid batteries from different battery manufacturers.

Finally, they consider as important factor the *Legislation* (F3) because it obliges producers to take responsibility for their batteries; therefore, regulations allow collectors to carry out sustainable economic activities.

Based on recyclers, the most important factors are those related to the Financial Aspects (F1) and Technological Aspects (F7). In fact, the positive financial result obtained from the recycling activities is a fundamental aspect that ensures the feasibility of materials recovery in pursuing the CLSC for LABs. The main reason that allows recyclers to consider the LAB a valuable product is the high price of lead in the London Metal Exchange (LME) market. Indeed, the actual price of lead allows recyclers to perform profitable activities.

The other important aspect is the technological one. In fact, the recycling process is simple and standard and it reflects the simplicity of the battery design. This allows recyclers to perform recycling activities without problems.

Moreover, recyclers give relevance to *Volume* (F2) and *Quality* (F8), as important factors that amplify the success of the recovery activities. In fact, Volume (F2) is fundamental because considering the remarkable quantity of LABs collected, recyclers can reach the maximum plant capacity and therefore they can exploit economies of scale. In addition, since the output of the recycling process is secondary lead with high purity level, recyclers become the first supplier of lead material in the market against mining companies. For this reason, the high importance given to *Quality* factor (F8).

Finally, they recognize the importance of *Companies Interactions* (F6) and *Legislation* (F3).

The former has relevance because through the collaboration of recyclers and battery manufacturers, new and better recycling technologies can be born.

The latter, instead, is seen in a similar way to the collectors' perspective: it allows having a large number of EOL LABs to be recycled.

4.2.3 LABs: evidence of factors overtime

In the table below are presented the results obtained through the performing of an analysis of each factor overtime. The aim is to identify the key milestones that affect the implementation of the CLSC for LABs. I decided to consider a timeline from the '90s to today, since the LAB is a quite old technology and a large time window allows to identify all the key facts that defined the success of this type of technology. The most affected factors are *Volume* (F2), *Legislation* (F3), *Organizational Set Up* (F4*),* *Infrastructure* (F5) and *Financial Aspects* (F7). However, in the table, for each factor is provided a brief description.

Table 10: Evidence of factors overtime.

Factors	1990/2000	2001/2010	2011/at present
F1: Technological Aspects	• No significant changes in both the lead-acid battery design and in the recycling technologies over the years. • In the battery, manufacturers reduce the amount of materials embedded and they work on battery performances: higher security, flexible designs and higher load speed. • For recycling technologies, there have been small improvements to reach higher level of operational efficiency in order to reduce the energy consumption and the environmental pollution.		
F2: Volume	• Growing battery sales in the market.	• Growing battery sales in the market.	• Growing battery sales in the market.
F3: Legislation	• **1988** (Italy): with the D.Lgs. 22/97 there is the definition of COBAT, the Italian taxation system engaged to manage EOL batteries. • **2000** (EU): with the Directive on End-of-Life Vehicles (2000/53/EC), the EC aims at making dismantling and and recycling of vehicles more environmentally friendly.	• **2006** (EU): with the Directive on Batteries (2006/66/EC), the EC wants to regulate the manufacture and disposal of batteries in the EU. • **2008** (Italy): the Italian government with the D.Lgs. 188/88, it implements the transposition of the Directive 2006/66/EC, focusing on the EPR.	• **2011** (Italy): there is the definition of CDCNPA (Centro di Coordinamento Nazionale Pile e Accumulatori) which has the task of coordinating the activities in order to make consistent and uniform procedures for collection throughout the national territory.
F4: Organizational Set Up	No evidence	• In **2006**, The introduction of the EPR with the Directive 2006/66/EC obliged battery manufacturers to take back their EOL products. Based on this, collectors and recyclers organize their activities in order to accomplish the manufacturer responsibilities (collective and an individual schemes).	
F5: Infrastructure	• From **1988** to **2008** in Italy there was only one network of collection owned by the State. • After the D.Lgs. 188/88 (**2008**), the liberalization of the market allows competition among players. Therefore, different collectors appears.		• In **2017**, the network is composed by 16 collective systems and 2 individual systems.

<table>
<tr><th>Factors</th><th>1990/2000</th><th>2001/2010</th><th>2011/at present</th></tr>
<tr><td>F6:
Companies Interactions</td><td>No evidence</td><td>No evidence</td><td>No evidence</td></tr>
<tr><td>F7:
Financial Aspects</td><td colspan="3">• In the period of reference, the price of lead is characterized by high volatility and therefore, it is registered an up and down trend (Figure 13).


Figure 13: lead price ($) over the years [1997/2013] LME.
• In 2017, the price ranges between 1898,31 € in August and 2131,97 € in November.</td></tr>
<tr><td>F8:
Quality</td><td>No evidence</td><td>• The quality of recycled lead was around a value of 95% of purity,</td><td>• 2017: with the implementation of some modifications in the recycling process, recyclers are able to reach the 99,97% of purity.</td></tr>
</table>

Chapter 5
Lithium-ion Battery Analysis

5.1 Lithium-ions battery description

Among the existing BEV technologies, the lithium-ions battery (LIB) is considered the best technology for sustainable transport due to its high energy and power per unit battery, which allowing it to be the lighter and smaller than other rechargeable batteries (figure 13).

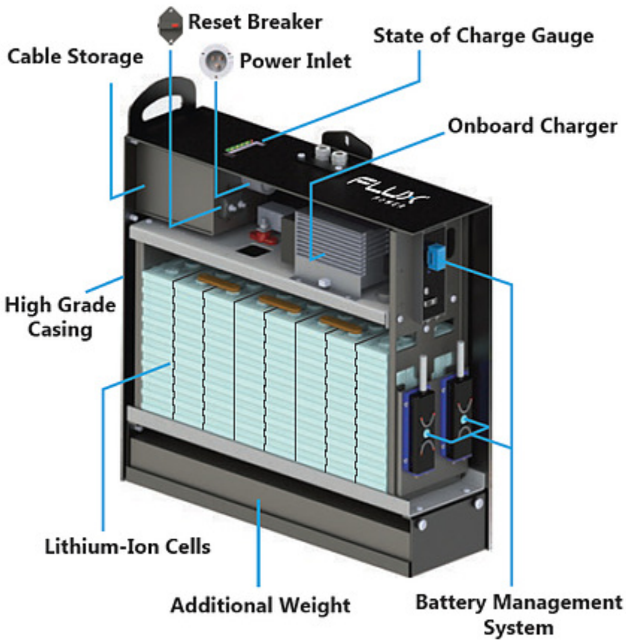


Figure 14: Main components of a LIB.

The lithium-ion battery is characterized by a high variety of chemical elements and compounds: H, Li, C, O, F, Al, Si, P, Ti, Mn, Fe, Co, Ni, Cu, Sn (Herrmann et al., 2012). It is a quite complex product because it consists of several LIB cells controlled by a battery management unit (BMU) to prevent deep discharge or overcharging and to monitor the cells' state of health.

From a functional view, each LIB cell is predominantly composed of four main components: a cathode, an anode, an electrolyte and a separator. In addition to these essentials, the LIB cells have a protective metal casing and covering plastic (see Table 11).

Table 11: Description of the main components of a LIB.

Components	Description
Electrodes	The electrodes are two: • Anode: negative alumina foil typically coated with carbon or graphite. • Cathode: positive copper foil coated with lithium/transition-metal oxides ($LiMnO_2$, $LiNiCoAlO_2$, $LiNiCoMnO_2$, $LiFePO_4$, $LiCoO_2$, etc.).
Separator	It is made by polymeric or ceramic materials and it has the function to prevent physical contact of the electrodes and to avoid internal short circuiting; Moreover, it provides an ionic conduction path for the liquid electrolyte.
Electrolyte	It is lithium salt dissolved in an organic aprotic solvent or solvent mixture, typically $Li[PF_6]$ (for safety and environmental risk).
Container	It is made by steel, alumina and plastics to protect the LIB cells.

One of the biggest concern linked with the EV boom is that this exponential diffusion could leave 11 million tons of EOL LIBs in need of recycling between now and 2030 (IEA, 2017).

5.2 Analysis of the Lithium-ions battery system

Based on interviews and secondary data of companies, and with the support of academic papers, in this section is presented the evidence of my list of factors affecting CLSC for lithium-ions battery.

In the table below (Table 12), the data collected from each company are presented. In order to assign the relevance that each factor has for the different supply chain actor, I use "xx" for factors that have huge relevance and "x" for factors with lower relevance. Finally, the empty parts refer to factors that are considered not relevant and that they are not taken into account.

Table 12: Evidence of factors according to the LIB actors interviewed ("xx" high relevance, "x" relevance).

Factors / Company	F1 Technological Aspects	F2 Volume	F3 Legislation	F4 Organizational Set Up	F5 Infrastructure	F6 Companies Interactions	F7 Financial Aspects	F8 Quality
M2	xx	x	xx	xx	x		x	xx
M3	xx		xx	xx				x
M4	xx		xx	xx	x	x	x	x
M5	xx		x	xx		x		x
M6	xx	x	xx	xx	x	xx	x	
M7	x		x	x		x		x
C1		x	x	x	xx	x	x	
C2			x	x	x	x	x	
C3		x	x	x	x	xx		
R1	xx	xx	x		x		xx	xx
R2	xx	xx	x	x	x	x	xx	x
R6	xx	xx	x		x	xx	xx	xx
R7	xx	xx	x		x	x	xx	x

5.2.1 LIBs: evidence of each factor

Technological Aspects (F1) is defined as one of the most critical aspects in pursuing the closed loop solution for LIBs.

M2 and M3 state that several factors contribute to making automotive Li-ion battery recycling more complicated than other types of batteries. First, LIBs have a wider variety of elements and compounds in each cell such as H, Li, C, Al, P, Fe, Co, Ni and others. The active materials are in a powdered form, coated into metal foil and these materials must be separated from each other during recycling. The battery is composed by more than 100 individual cells (a Tesla Electric Vehicle Battery has 5000 cells) and within the cells, the chemical compositions of active materials (especially the cathode) vary with manufacturer and battery function. Therefore, they maybe never be standardized; the most common cathode technologies are $LiMnO_2$, $LiNiCoAlO_2$, $LiNiCoMnO_2$, $LiFePO_4$ and $LiCoO_2$.

The result is that, in the market, there are different battery designs. In fact, there is not a standardization of the product but each manufacturer has its own version characterized by specific levels of performances (R1 and R2). M4 adds that having so many LIB technologies in the market, recycling them will bring many problems because each technology needs to be manage in a separated and proper way.

The same issue comes out talking with battery recyclers. R2 explained that in the market, so far, it is not clear which variant of the lithium-ions battery technology will become prevalent and for this reason recyclers are cautious in making investments for LIB recycling technologies.

Due to the early development stage of the EV market and the variety of battery technologies, there is not a preferred recycling technology. These technologies are usually multi-stage co-production processes and they embrace both automatic and manual disassembly steps. Moreover, the volume and the type of materials that can be recovered from LIBs differ widely between available battery variants.

For example, R1 and R6 perform recycling activities following the hydrometallurgical process; R2 and R7 use the pyro-metallurgical one.

In the table below (Table 13), there are presented the main features of the two processes.

Table 13: Features of the recycling process with positive and negative aspects (Hanisch et al., 2015; Heelan et al., 2016).

	Recycling Process	Positive Aspects	Negative Aspects
Pyro-metallurgical recycling process *Umicore* (R7)	The LIB is dismantled and then smelted in a high temperature shaft furnace from which alloy and slag are obtained (each composed by a mix of materials). By leaching the alloy: there is the recovery of copper, cobalt, iron and nickel. By cleaning up the slag: there is the avoidance of the release of potentially toxic by-products.	• High productivity • Quick production of a metal phase • No waste water • No sludge to dump	• No recovery of aluminum and lithium because is neither economical nor energy efficient. • Intensive use of electrical energy • Gas emission control is needed • Slag generation • Less suitable for small scale operations • - Very expensive
Hydrometallurgical (used from mechanical or pyro) *Accurec* (R1) *Recupyl* (R6) *Retriev*	The LIB is firstly dismantled to separate plastic and iron scraps from active electrode materials by physical separation using crushing, sieving, and magnetic separation. Then, in order to recover valuable materials like lithium a sequence of educts leaching, crystallization and precipitation must be performed.	• Extraction of pure metals • High recycling rate • High selectivity • It is the only way for Li-recycling • Carbon recovered as product • Minimal off-gas generation • Low energy consumption • Reduced environmental impact	• Variety of chemical reagents used • Water requirement and need for waste water treatment • Low kinetics • Loss of Fe and Al

The pyro-metallurgy is the most common solution that allows recovering the most valuable materials through high temperature melting processes. R7 highlights “nowadays there is no system that is able to operate for continuous 24h with a stream of lithium batteries” (F2). In fact, R7, one of the recyclers of LIBs leader in Europe,

when it does the recovery, it always divides the EOL LIBs into batches in order to maximize economic (F7) and operational benefits.
R2, instead, underlines that it performs only "standard" recycling activities that allow to recover the most valuable materials (cobalt and nickel) (F7). This decision was driven by the possibility to reduce the uncertainty about the output of the recycling activities and the maximization of the profit (F7). Indeed, all the existing recyclers (R1, R2, R6 and R7) perform recycling activities only if the result ensures a positive margin. Based on this, recyclers extract materials following a priority list: from the material with the higher value to the material with the lower one. In fact, in these years, much of the lithium-ion battery recycling so far has been motivated by the extraction of cobalt from the cathode, along with, to a lesser extent, nickel and copper. The reason is the high value of these elements that makes recycling economically attractive (F7).

R1, instead, has developed a new innovative process technology that not only allows to recover high valuable materials with minimum costs (F7), but also allows to reduce level of emissions and to prevent dangers related to health and safety issues concerning employees and environment. In fact, although with the recycling of LIBs it is possible to reduce the volume of waste products containing toxic materials and the negative impact of mining activities, the recycling process (both pyro-metallurgical and hydrometallurgical) are characterized by high level of pollutions.

Moreover, Hanisch et al. (2015) classified in three groups the different dangers which can occur performing LIB recycling activities and they are: electrical dangers, fire and explosion dangers and chemical dangers. According to this classification, R2 added that managing cathodes is a dangerous activity because when alkaline, flammable and slightly explosive metals are exposed to air or to water, it occurs a violent reaction.

The result is that the technology both in term of LIB design and recycling technology is seen as a bottleneck for the success of the CLSC.

With this exponential EVs diffusion, not only battery manufacturers produce lithium-ions batteries but also some car manufacturers entered into this market: M6 and M7 are two car manufacturers which are producing their own EV batteries. Based on the list of bottlenecks for the proper performing of recycling activities, car/battery manufacturers found another solution to manage this flow of waste batteries. Instead of finding a solution for LIB with recycling, they are stretching the product life cycle with an additional phase: the reuse. Since nowadays there is not a well performing recycling technology car manufacturers stretch the life of the battery as a storage for renewable energy sources. In fact, M7 explained that the fundamental problem of LIB is that while the cost of fully recycling a battery is falling toward €1 per kilo, the value of the raw materials that can be reclaimed is only a third of that (F7). Therefore, in order to “solve the problem” of huge volume of EOL LIB which have no a destination, as other car manufacturers did, M7 has partnered with a power management firm with the aim of reusing its car batteries for home energy storage.

Finally, in the recent years, a lot of experiments are conducted in order to identify a solution for the recycling of automotive LIB. Among them, M4 says that in Pennsylvania (USA) some researchers discovered that there are in nature mushrooms capable of making the "lithium-ion battery" biodegradable. Now there is the need to use highly polluting chemicals to dispose this kind of battery, but with this discovery, it would be possible to use only three different mushrooms. Indeed, these mushrooms are characterized by a curious ability: extract metals from waste materials. These acids are able to return a good percentage of the original metals: over 80% for lithium, and 48% for cobalt.

The next step now consists in finding a way to recover metals from the liquid acid environment in which they are immersed at the end of the process. If the whole procedure were finally finalized, it would be a great achievement: not only it would allow reducing pollution into the environment, but also it would save valuable resources, which in any case are not inexhaustible and whose demand is constantly increasing.

The growing market for EVs and the uncertain length of the useful life of LIBs result in an uncertain and dynamic *Volume* (F2) of spent Li-ion batteries. The drive to replace polluting petrol and diesel cars with a new breed of EVs has gathered momentum in recent years. But there is an unanswered environmental question at the heart of the EV movement: “what on earth to do with their half-ton lithium-ion batteries when they wear out?” (The Guardian, 2017). The number of electric cars in the world passed the 2 millions last year (Figure 15) and the International Energy Agency (2017) estimates there will be 140 million of EVs globally by 2030 if countries meet Paris climate agreement targets. (Figure 16) shows the results of an analysis conducted by the IEA in 2017 (Gobal EV Outlook 2017) in which based on the different scenarios analyzed they define forecasts about the EV diffusion.

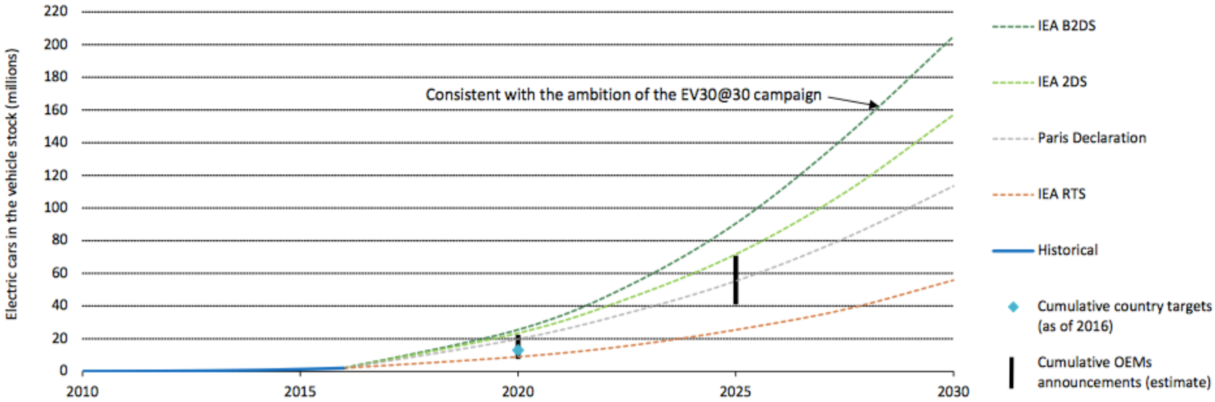


Figure 15: Deployment scenarios for the stock of electric cars to 2030 by the International Energy Agency (2017).

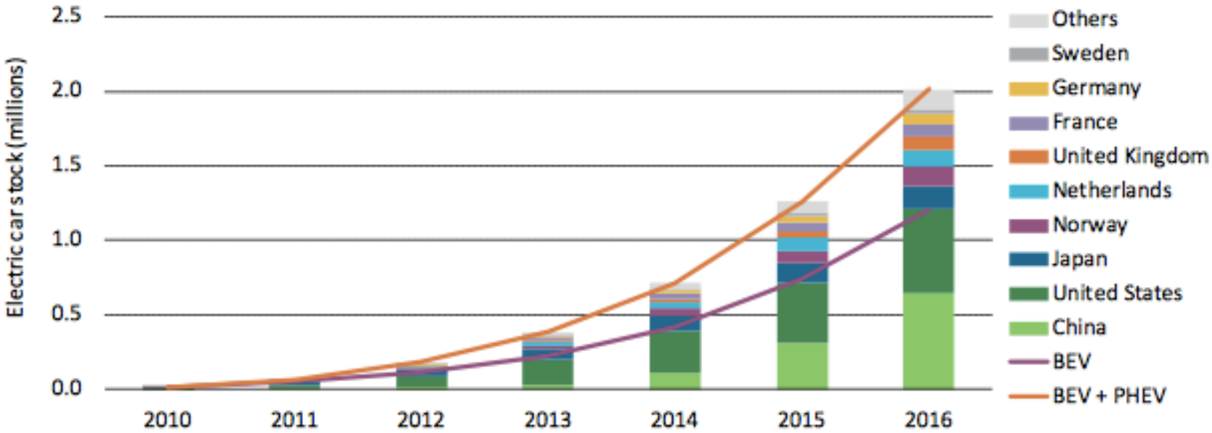


Figure 16: Evolution of the global electric car stock, 2010-2016 by The International Energy Agency. (BEV: battery electric vehicle; PHEV: plug-in hybrid electric vehicles).

Automotive LIBs have only been in commercial use for about some years and it will take some time until they reach large volumes (M2 and M6). Further, their long product life (10 years) means that not nearly enough batteries have reached the end of their lives to support large-scale recycling plants

Indeed, the current levels of lithium-ion batteries collected in Europe are very low (C3) and no precise statistics are available (CDCNPA).

Recyclers, in this uncertain scenario, are not aware about the future flows of waste LIBs. In fact, R2 says that it is very difficult to predict what type of batteries will be available in the future due to the continuous development and changes in view of the overall design, the use of new materials in the cathodes and the assembly techniques for the production of Li-ion batteries (F1).

Wang et al. (2013) claims that more than half a million end-of-life EVs' battery packs will need to be treated by 2022. The problem is that there is no precise information about which types of Li-ion batteries will be available for recycling.

R1 defines recycling activities a fundamental step in the CLSC perspective but it adds that with these low volumes of EOL lithium-ions batteries, both a satisfactory economic result (F7) and an operational efficiency are difficult to achieve. Indeed, LIB is an emerging technology that only in the last years it is experiencing a huge adoption. Therefore, since the useful life is around 10 years, only in a couple of years, huge volumes are expected. This is a problem for recyclers because with the actual volume of EOL LIBs firstly they are not able to exploit economies of scale (F7) and secondly there is no security to set medium and long terms investments (C3, R2).

Moreover, the future volumes of products available for recycling may be less than those expected because a considerable part of EOL LIBs could be used for the secondary use as energy storage (M6, C2). This alternative is seen by EVs manufacturers, who are also working on the lithium-ions battery industry, as a way to solve the problem of how to deal with EOL LIBs. CDCNPA and R3 highlight that existing regulations (F3) lack to regulate these activities.

In addition, another source of volume uncertainty is related to the illegal flow of EOL LIBs (C1, CDCNPA). Indeed, flows of batteries are exported to be discarded in an unsustainable way, without following the practices established by law (F3). This affects recyclers because the volume of EOL LIBs is lower, but in particular it generates negative impacts on the environment. Lithium-ion batteries contain hazardous materials: the improper disposal will expose to serious health and environmental risks.

Instead, if we consider the output of the recycling process of LIBs, according to the market price of the different materials (F7) only cobalt, copper and nickel are recovered by all the LIB recyclers (R1, R2, R6 and R7). Only R6 with its patented hydrometallurgical recycling process is able to process EOL LIBs into valuable secondary raw materials including lithium.

In Europe, no precise and reliable numbers are available about flows of recovered lithium. So far, the only available number refers to the "End of Life recycling input rate" (EOL-RIR) provided by the European Commission that is equal to 0% (European Commission, 2017b). Indeed, while commercial smelting processes such as R7 can easily recover many metals, they can not directly recover the vital lithium, which ends up in a mixed byproduct. R7 says that it can reclaim lithium from the byproduct, but each extra process adds cost (F7). This means that while electric vehicle batteries might be taken to recycling facilities, there is no guarantee the lithium itself will be recovered if it does not pay to do so (R2 and R6).

Furthermore, M2 and M5 say that in case there is recycled lithium, between the virgin and the recycled lithium, they would choose the less expensive one (F7). Therefore, the CLSC is problematic in any cases. Even if lithium is recycled, it would not be chosen as material for the production of new LIBs. Indeed, high costs are associated to the recovery of lithium and the market price of lithium is not high enough to recover such costs.

Legislation (F3) is the only factor cited by all the companies and it is considered an indispensable aspect for a formal management of spent LIBs in a CLSC.
Lithium-ions battery manufacturers describe this factor in terms of obligation that they have to fulfil (M2, M3 and M4). In fact, the European Commission, following the philosophy of the CLSC, developed regulations (Battery Directive 2006/66/EC and further integrations) concerning the mandatory performing of collection, treatment, recycling and disposal activities for EOL automotive batteries (LABs, LIBs, Ni-Cd batteries etc.). In particular, the Battery Directive (2006) is pushing efforts towards CLSC solutions in order to solve different issues:

- ✓ ensure supply security of valuable materials like cobalt, copper, nickel and lithium in order to keep materials within European borders;
- ✓ reduce the quantity of EOL batteries sent lo landfill;
- ✓ prevent possible environmental and human health pollution.

The Directive is seen challenging for each actor involved in the system:

- ✓ Manufacturers of LIBs are obliged to deal with the take-back of batteries (introduction of the EPR, F4) placed on the market following the aims of protecting the environment, avoiding landfill, and preventing contamination of water (M2 and M4). As for the other battery technologies, M5 underlines that in order to fulfil its responsibility has to pay (F7) a fee to collectors based on the amount of batteries sold in the market. M5 and R2 add that the criterion for the definition of fees that manufacturers have to pay is not so correct. In the market, there are different types of automotive LIBs each one characterized by different materials, compounds, chemicals and designs. Therefore, the fee paid by manufacturers should be based on a set of parameters and not only on volume. In fact, at each battery technology corresponds a specific recycling process that has its own level of costs.

- ✓ Collectors, instead, have to ensure the collection of batteries. C1, C2 and C3 are hesitant in achieving this goal. Indeed, the lack of details of collection for each battery technology (e.g. specific targets for each type of battery) is particularly underlined by C2. Also C3 referred to the issue that legislations are not complete. From their point of view, the problem is that they are not able neither to provide precise rules to follow for this emerging technology nor to help lithium-ions battery manufacturers to fulfil their responsibility (F4).
- ✓ Finally, recyclers have to achieve the recycling rate of 50% of the lithium-ions battery mass. Based on the existing technologies, all the recyclers (R1, R2, R6 and R7) have no problems to reach this objective: R6 is able to achieve a recycling rate of the 65% of the battery mass. Therefore, since there are not specific targets for recovery of particular materials, some materials like lithium may not be recycled. In addition, at present, there are no regulations regarding the adoption of particular recycling technologies for the recovery of LIBs. This condition is considered positively by recyclers (R1 and R6), who would face no restrictions in process design. However, they face the possibility that restrictive regulations could later be imposed and therefore, processes must be designed to be compliant with anticipated regulations. In addition, recycling technologies are still evolving and it could happen that the recycling process designed for a specific design or chemistry could become irrelevant (R2).
- ✓ For car manufacturers, the scenario is more challenging. Until 2015, vehicles had to be overall 85% recoverable by vehicle weight, of which 80% is actually reusable or recyclable. From 2016, vehicles have to be 95% recoverable, of which 85% reusable or recyclable (The End of Life Vehicles Directive, 2000/53/EC and further integrations). Therefore, based on the % of recovery and considering the importance that the battery has in the car, the LIB (as all the other battery technologies) must be recycled in order to meet the regulation (M6 and M7).

As mentioned in F3, *Organizational Set Up* (F4) is an enabling condition that drives the implementation of the CLSC for EV LIBs. Indeed, after the introduction of "The End of Life Directive" and "The Battery Directive" (F3), the involvement of car manufacturers and battery manufacturers in the product life cycle is changed. As it happens for LABs, M4 and M5 highlighted how the introduction of the EPR altered the system. Indeed, LIB manufacturers have to take back their EOL products and in order to fulfil this responsibility, they pay a third actor in charge of performing logistics activities. The collector is seen the means through which EOL products are available at the recycler site in order to be recycled.

Automotive LIBs are an emerging technology and, so far, no precise rules have been defined (M2). The battery manufacturer has to pay a fee based on the volume of batteries placed on the market. The problem for this technology is that there are a large variety of technologies each one characterized by different materials, compounds, chemicals and designs.

As for the other actors involved in pursuing the closed loop, collectors and recyclers, are responsible to fulfil the manufacturers' obligations. They see the EPR as a way to make money (C1, C2, R2).

As regards the network structure, in Europe, there are three different typologies of systems, which try to answer to the fulfilment of the EPR (CDCNPA): the taxation system, the compulsory consortium system and the competitive collection system (in place in Italy).

Focusing on the last option, manufacturers can come up with two different collection system configurations: an individual or a collective one. In the individual the manufacturer has directly to be able to manage the logistics activities; indeed, in the collective network, there is a third party that has the responsibilities to perform such activities and the battery manufacturers share all end-of-life costs (C1). Thus, battery manufacturers (M2, M4) are more oriented to exploit the collective system as the management of collection activities is complicated and expensive. Indeed, M6 a battery and car manufacturer, in order to meet its responsibilities, it organized a specific network. This highly horizontal organization brings together all the skills to deal with upstream and downstream processes. The activity is managed at two levels: upstream, which seeks eco-design solutions, and downstream, which involves monitoring the collection and treatment of end of life vehicles and LIBs. This work is conducted in close collaboration (F6) with partners such as suppliers, recycling operators and manufacturers associations. Moreover, M6 decided to set a contract for the entire European market with a single and efficient partner.

In pursuing the closed loop perspective, the *Infrastructure* (F5) plays a fundamental role since it allows the physical link between Li-ions battery manufacturers and recyclers (C2, R2). Before the introduction of EV LIBs in the market, a collection network for EOL LABs, EOL WEEE and other products was already in place. Therefore, the already established collectors decided to enlarge their activities through the collection of EOL LIBs. Indeed, in the same infrastructure they manage different end-of-life products. C1, one of the most important Italian collectors, is responsible for the collection of EOL batteries and in order to exploit economies of scale (F7) it also collects portable batteries, accumulators, photovoltaic panels and waste tires. Although these products are easily recognizable and distinguishable, the same can not be said for the different typologies of battery technologies (F1). The contamination of the input stream may be the result of mistakes due to the fact that many current Li-ion batteries are indistinguishable from lead-acid batteries (M4, R2, R6). To confirm this, recent events happened where LABs have been included into the LIBs input stream and at the recycling plant fires and explosions occurred. R2

C1, C2 and C3 emphasized that, in Italy, a recycling system for LIB is missing. After the performing of the collection activities, collectors send the collected EOL LIBs to European recycling plant. Indeed, in Italy no plants able to recycle LIBs are present. M4 states that if the collection system is well-performing, the recycling system for LIBs is missing at all.

In Europe, the are few players that ensure the recycling of LIB. In the table below are presented the most relevant European recyclers with the details of recycling technology and recycling capacity (Lebedeva et al., 2016).

Table 14: Most relevant European recyclers.

Company Name	**Recycling Process**	**Recycling Capacity** (Tons of batteries per year)
UMICORE Battery Recycling	Pyro-metallurgy	7000
ACCUREC Recycling GmbH	Pyro-metallurgy with hydrometallurgy	1500-2000
Recupyl S.A.	Hydrometallurgy	110
SNAM	Pyro-metallurgy with mechanical separation and hydrometallurgy	300

CDCNPA underlines that the whole recycling infrastructure for LIBs is only developing in recent years, given the exponential growth of electric vehicles in the market. Moreover, recyclers are cautious in making new plants and recycling technologies investments (F1). Indeed, recyclers are worried about the possibility that restrictive regulations (F3) could later be imposed making new investments obsoleted. In addition, recycling technologies are still evolving and it could happen that the recycling process (F1) designed for a specific design or chemistry could become irrelevant (R2).

A factor that has high potential for closing the loop for automotive LIB is the *Companies Interactions* factor (F6). Indeed, since the system is characterized by important criticalities to overcome, all the actors interviewed agree in defining collaboration, transparency and information sharing as key enablers to implement a successful CLSC.

LIBs manufacturers (M4 and M5) and recyclers (R1, R6 and R7) are collaborating in order to define easy ways to disassemble and recycle batteries. They are also trying to develop recycling technologies able to recover high valuable materials (including lithium) in an economic and environmental way. For example, R6 have formed partnerships with the manufacturers of batteries and electric vehicles in order to design eco-friendly batteries that can be recycled more easily and to develop high-yield processes to recycle next-generation batteries (F1). M6 developed a network with partners such as suppliers, recycling operators and manufacturers associations in order to face the LIBs recycling challenges.

Furthermore, in Italy from 2014, C1 with a group of recyclers in collaboration with the CNR (Consiglio Nazionale delle Ricerche) are working on a research project to identify an effective, safe and eco-sustainable system that allows the complete recovery of the materials that make up the LIB.

Moreover, the actors interviewed put also high emphasis on the importance of sharing information between:

- ✓ Manufacturers and Collectors; these actors can share information about future expected volume of EOL batteries based on data about EV sold in the market, expected product returns etc. They can share information about the different battery technologies in order to avoid mistakes and problems of mixing flows (LABs and LIBs) (M5, C3);
- ✓ Collectors and recyclers; they can share visibility on the flows in order to be able to prevent accidents due the contamination of flows of collected batteries. This would allow to avoid explosions at the recycling site (C2, C3, R1, R2);
- ✓ Recyclers and Manufacturers; according to the statement of M7: "we consider right from the very early planning phase whether certain materials have proven particularly suitable for recycling purposes in the past", the sharing on knowledge and information is fundamental for further developments in the definition of the proper battery design (M7, R6).

The *Financial Aspects* (F7) is an important dimension that affects the decisions taken by lithium-ions batteries manufacturers and in particular recyclers. The interviewees define that the market price of materials is an important driver of the system. In fact, the recyclers recover from EOL LIBs only the materials that are able to cover the costs of the recycling process. For example, R1 and R7 recover only cobalt, nickel and copper since their high price are able to ensure the economic feasibility of recycling activities (see Figure 17). Among the other materials in the battery, lithium is not recovered by the majority of recyclers due to the high costs of the activities needed to perform. Only R6, in its small plant, is able to obtain lithium through hydrometallurgical processes. Although these processes allow to recover lithium with high metal purity (F8), it is very expensive. Moreover, another important issue that recyclers must consider is that battery manufacturers are going to produce LIBs with cheaper materials. This adds further criticalities at the problem that recyclers are facing: the economic feasibility of the recycling activities.

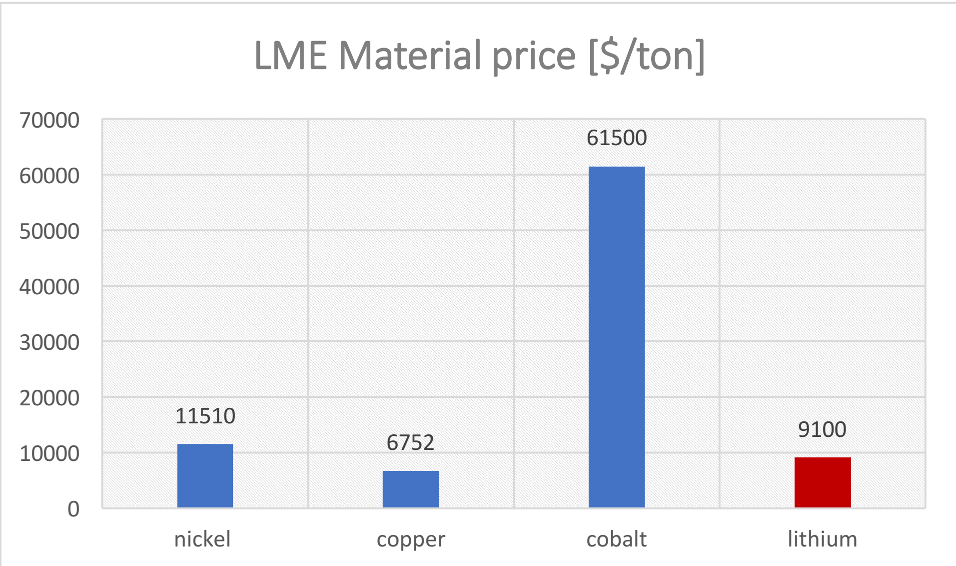


Figure 15: Comparison between materials market price (LME, November 2017.)

Focusing on the LIB manufacturers, they are economic actors that take decisions following the profit maximization principle. For this reason, during the procurement phase of raw materials for the production of batteries, they buy the materials with the lowest price. M2 and M4 say that for cobalt, nickel and copper there are periods in the year in which secondary materials are convenient than the virgin ones. They add that for lithium the situation is different: the recycled lithium is too expensive compared to the virgin one. Therefore, M4 says that the possibility to close the loop for this material is very challenging especially due to the financial aspect. However, with the increasing number of EVs entering the market in the next future and with a significant supply crunch, recycling is expected to be a significant factor for consideration in effective material supply for battery production. “This is a big issue that needs to be solved” says M2.

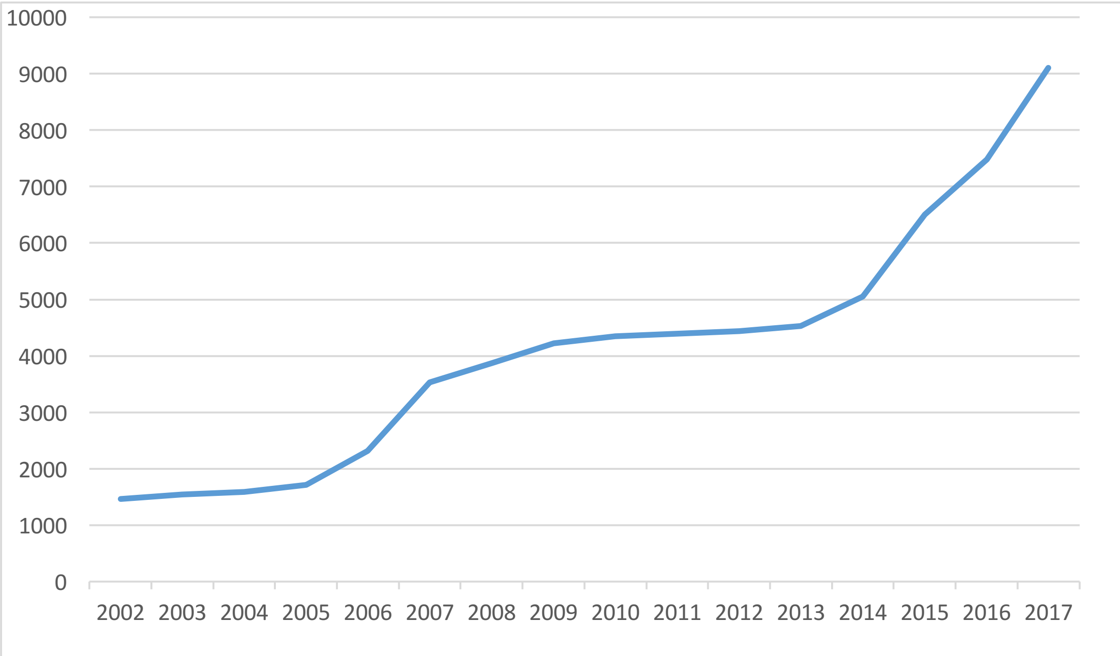


Figure 16: Lithium market price from 2002 to 2017 [$/ton].

Collectors, instead, are not so involved in this issue because whether or not the product is entirely recycled, they have to carry out the needed logistics activities to fulfil the manufacturers’ responsibility (F4).

Furthermore, M7 states that dedicated processes and small scale recycling plants closer to EV manufacturers are likely to be the trend in the next future. The long-term nature of financial investments required by market participants to develop specialized waste disposal services is the main challenge hindering the industry.

For the success of the CLSC not only the price of the recovered material is important, but also its *Quality* (F8) plays a relevant role (M4 and M5). Indeed, high standards of material purity are required for the production of LIB (M3). However, due to technological constraints (F1) and financial considerations (F7), the available recycled lithium is scant (M2, R1, R6). Therefore, the only viable option of battery manufacturers is to buy virgin lithium.

Nevertheless, R2 states that a possible problem of purity could affect the recycled lithium. Since in the lithium-ion battery there are many materials and different chemicals, the recover lithium could be affected by problems of contamination. Therefore, even though the recycled lithium in the market would be available in large quantities, no battery manufacturers will use recovered lithium. In fact, the recovered lithium is used for non-automotive purposes, such as construction, or sold in the open-market. In conclusion, in order to fulfil, technical requirements, refining activities are needed. This implies additional technologies (F1) and most of all additional costs (F7).

5.2.2 LIBs: evidence of factors for the different SC positions

Based on each supply chain position, in the table below (Table 15) are presented the degrees of importance of each single factor for closing the loop of LIBs.

I defined three different categories. Each category is associated with a color:

- ✓ **Green**: huge importance for the SC position;
- ✓ **Yellow**: relevant for the SC position;
- ✓ **White**: no evidence.

Table 15: Evidence of factors for the different SC positions.

Factors / Company	F1 Technological Aspects	F2 Volume	F3 Legislation	F4 Organizational Set Up	F5 Infrastructure	F6 Companies Interactions	F7 Financial Aspects	F8 Quality
M2	xx	x	xx	xx	x		x	xx
M3	xx		xx	xx				x
M4	xx		xx	xx	x	x	x	x
M5	xx		x	xx		x		x
M6	xx	x	xx	xx	x	xx	x	
M7	x		x	x		x		x
C1		x	x	x	xx	x	x	
C2			x	x	x	x	x	
C3		x	x	x	x	xx		
R1	xx	xx	x		x		xx	xx
R2	xx	xx	x	x	x	x	xx	x

Factors Company	F1 Technological Aspects	F2 Volume	F3 Legislation	F4 Organizational Set Up	F5 Infrastructure	F6 Companies Interactions	F7 Financial Aspects	F8 Quality
R6	xx	xx	x		x	xx	xx	xx
R7	xx	xx	x		x	x	xx	x

Based on the battery and EV/battery manufacturer perspective, the most relevant factors are *Technological Aspects* (F1), *Legislation* (F3) and *Organizational Set Up* (F4).

F1 is seen as a criticality because recyclers with the available recycling technologies are not able to recover all the materials embedded in the lithium-ion battery. The main reasons are: the high variety of materials and chemicals in the battery, the presence of different designs and the value of materials.

F3 and F4, instead, represent the drivers that force them to perform additional activities for the recovery of their EOL batteries. They have to fulfil these obligations otherwise, if they fail to comply with them, they have to face costly sanctions.

Moreover, for battery manufacturers, *Quality* (F8) (if things do not change) is seen as a future bottleneck condition due to the high variety of materials and chemicals in batteries (problem of contamination).

Instead, for EV/battery manufacturers (M6/M7), *Companies Interactions* (F6) acquires huge importance as enabler of collaborations with other actors in order to solve criticalities both at the production and at the recycling stage.

Based on collectors, according to their role in the CLSC, the most relevant factors are those related to the functioning of network system and to the definition of different relationships among companies.

Indeed, *Organizational Set Up* (F4), *Infrastructure* (F5) and *Companies Interactions* (F6) are fundamental for the proper implementation of the CLSC.

Collectors can decide to share information with battery manufacturers in order to properly manage the collection activities to reach high efficiency and high service level. Moreover, collectors can avoid the mixing of LIBs with LABs with the sharing of information with battery recyclers. This allow reducing the risk of fires and explosions at the recycling facility.

Finally, they consider as important factor the *Legislation* (F3) because it obliges producers to take responsibility for their batteries; therefore, regulations allow collectors to carry out sustainable economic activities.

Based on recyclers, the most important factors are those related to the *Technological Aspects* (F1), the *Volume* (F2) and the *Financial Aspects* (F7).

F1, with the actual recycling technologies, is considered a bottleneck. There is not a technology able to recover all the materials in the battery achieving satisfactory results in terms of efficiency, economic feasibility and environmental pollution. The main reason is the presence of a high variety of different lithium-ions battery technologies characterized by different materials and chemicals. Therefore, recyclers in order to perform economic feasible activities (F7), according to the value of each material, prioritize the recovery of materials that cover the production costs.

Moreover, the product complexity affects also the *Quality* (F8) of recovered materials. In fact, with the actual technologies, the level of purity of recovered materials (in particular for lithium) is not acceptable for the production of new batteries.

The other element of criticality is F2 because the flows of EOL LIBs are not big enough to allow reaching economies of scale. Nowadays, activities are managed in batches and it means losing of money and operational efficiency. However, it is a momentary issue. With the exponential diffusion of EVs, recyclers are confident that in a few years, the volume of EOL LIBs will increase.

Finally, they recognize the importance of *Companies Interactions* (F6) and *Legislation* (F3).

The former (F6) has relevance because recyclers and battery manufacturers can collaborate in the definition of battery designs easy to recycle and recycling technologies able to recover all the materials embedded in the battery. Thus, the collaboration can boost the sharing of technical knowledge and information so that both parties can benefit from it.

The latter (F3) is considered as an enabling condition because ensure the availability of high volumes of LIB (Battery Directive and EPR). However, regulations are also a factor of uncertainty because, in the future, possible laws could make outdated actions and investments (new technologies and new plant capacity, *Infrastructure* (F5)) made so far.

5.2.3 LIBs: evidence of factors overtime

In the table below are presented the results obtained through the performing of an analysis of each factor overtime. The aim is to identify the key milestones that affect the implementation of the CLSC for LIBs. Although the automotive lithium-ions has been on the market for a few years, I decided to keep the same timeline used for lead-acid battery analysis in order to ensure consistency. The most affected factors are *Volume* (F2), *Legislation* (F3), *Organizational Set Up* (F4*), Infrastructure* (F5) and *Financial Aspects* (F7). However, in the table, for each factor is provided a brief description.

Table 16: Evidence of factors overtime.

Factors	1990/2000	2001/2010	2011/at present
F1: Technological Aspects	No evidence	• The automotive lithium-ion battery technology is a recent technology. In the market there are different typologies with different materials and chemicals. In the last years, manufacturers are trying to reduce the amount of materials embedded. • For recycling technologies, there are several processes quite expensive and characterized by high energy consumption and environmental pollutions. In the last years, researchers are trying to define better processes able to recover all the materials embedded in LIBs. An example, mushrooms capable of making the "lithium-ion battery" biodegradable • **2014:** CNR + COBAT (project)	
F2: Volume	No evidence	No evidence	• LIBs are becoming a common replacement for the lead-acid batteries. The world's appetite for lithium-ion batteries is on a steep rise. • In the fall of **2015**, the number of electric vehicles on the road passed the one million mark, their sales driven by growing markets in China and Norway. Millions more could be sold in the next decade.

Factors	1990/2000	2001/2010	2011/at present
F3: Legislation	• **1988** (Italy): with the D.Lgs. 22/97 there is the definition of COBAT, the Italian taxation system engaged to manage EOL batteries. • **2000** (EU): with the Directive on End-of-Life Vehicles (2000/53/EC), the EC aims at making dismantling and and recycling of vehicles more environmentally friendly.	• **2006** (EU): with the Directive on Batteries (2006/66/EC), the EC wants to regulate the manufacture and disposal of batteries in the EU. • **2008** (Italy): the Italian government with the D.Lgs. 188/88, it implements the transposition of the Directive 2006/66/EC, focusing on the EPR.	• **2011** (Italy): there is the definition of CDCNPA (Centro di Coordinamento Nazionale Pile e Accumulatori) which has the task of coordinating the activities in order to make consistent and uniform procedures for collection throughout the national territory.
F4: Organizational Set Up		• In **2006**, The introduction of the EPR with the Directive 2006/66/EC obliged battery manufacturers to take back their EOL products. Based on this, collectors and recyclers organize their activities in order to accomplish the manufacturer responsibilities (collective and an individual schemes).	
F5: Infrastructure	• From **1988** to **2008** in Italy there was only one network of collection owned by the State. • After the D.Lgs. 188/88 (**2008**), the liberalization of the market allows competition among players. Therefore, different collectors appears.		• In **2017**, the network is composed by 16 collective systems and 2 individual systems. • In terms of LIBs recycling capacity, in Italy there are no plants so far. Instead, in Europe, the plants able to manage LIBs are few (Umicore, Accurec, Recupyl, SNAM)

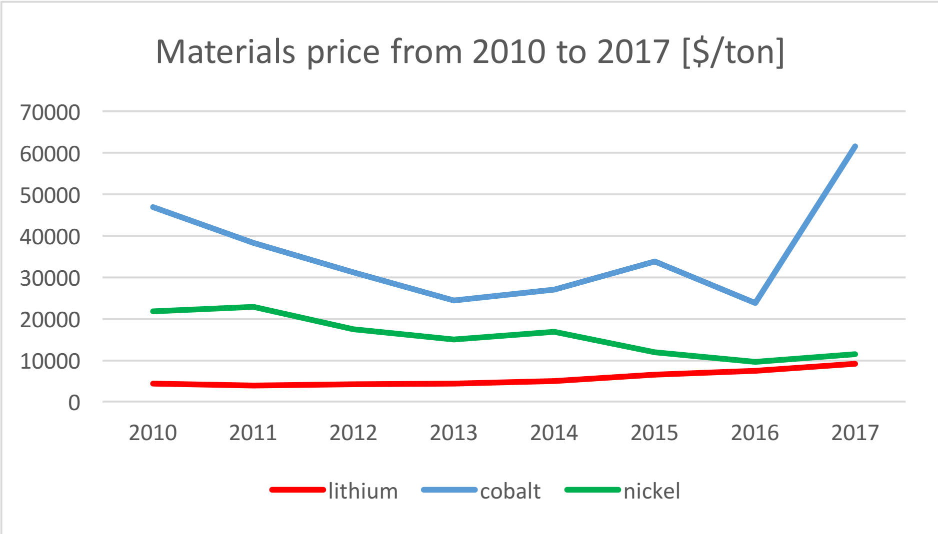
<table>
<tr><th>Factors</th><th>1990/2000</th><th>2001/2010</th><th>2011/at present</th></tr>
<tr><td>F6:
Companies Interactions</td><td>No evidence</td><td>No evidence</td><td>• In the last years, collaboration and exchange of knowledge and information have become fundamental.
• For example, in Italy, in 2014: Cobat + CNR → new recycling technology for spent LIBs.</td></tr>
<tr><td>F7:
Financial Aspects</td><td colspan="3">• The market price of materials drives the economic feasibility of the overall system. In the period of reference, cobalt, nickel and lithium are characterized by a high volatility of prices.


Figure 17: Material market price comparison (Source: metalary.com)</td></tr>
<tr><td>F8:
Quality</td><td>No evidence</td><td>No evidence</td><td>• There are no important evolution about the quality of recovered materials.</td></tr>
</table>

Chapter 6
Comparative analysis of LAB and LIB system

Based on information presented in Chapter 4 and Chapter 5 about LAB and LIB systems, the aim of this chapter is to provide a comparative analysis between the two systems.

First of all, in Table 17, I offer a comparison between the evidence of factors affecting the CLSC for the two systems according to the different supply chain positions (manufacturers, collectors and recyclers). In order to distinguish the different degrees of evidence that each supply chain position of the two systems provides for each factor, I decide to use “x” for factors with relevance and “xx” for factors with high relevance. The decision to put “x” or “xx” is based on the results shown in the previous Chapters 4 and 5, in Table 9 and in Table 15 (at the yellow cells is assigned an “x” and at the green cells is assigned a “xx”). These are aggregated results and therefore, if a cell is blank it does not mean that the factor is not consider by all the actors. For example, for F5, the factor that refers to the *Infrastructure*, half of LAB and LIB manufacturers commented on this but compared to other factors it has lower relevance. The same can be said about F7 (*Financial Aspects*) in particular on collectors: some of them mention this factor but compared with the others it is not consider so important. Therefore, regarding the cells that in Table 17 are blank, it does not mean that they are absolutely irrelevant but according to a prioritization of relevance they are less important.

The table shows that only few factors, according to the different SC positions, have differences.

This means that the same factor, following the same objective for the two battery system (the CLSC of battery) can have different degree of importance if compared with the other factors.

In particular, the main differences are among LAB and LIB manufacturers.

If we consider the *Financial Aspects,* the former ones assign high relevance on this factor since the competitive price of recycled lead compared to the virgin one allows to gain economic benefits. The latter ones, instead, although some of them mention this factor as important to the development of a CLSC for lithium-ion batteries, compared to the other factors it has less relevance. Indeed, LIB manufacturers give more emphasis on *Technological Aspects* since the complexity of the LIB impairs the close loop perspective compared with the LAB that is a simple and standard product. Moreover, LIB manufacturers consider important for closing the loop the *Companies Interactions* factor since the possibility to establish relationships between actors of different supply chain position is seen as a way to solve criticalities linked with the LIB complexity (e.g. sharing of information and collaboration between battery manufacturers and recyclers). Finally, *Quality* is considered relevant for the LIB manufacturers due to the problem of contamination of recycled materials, although this problem is currently not very evident given the low availability of EOL LIBs.

Instead, the collectors (C-LAB and C-LIB) do not present differences in relevance of factors in CLSC. This is due to the fact that the collectors interviewed for the two different systems of batteries are the same. Indeed, their involvement in the system consists in performing collection activities both for LAB and LIB manufacturers. Although collectors deal with two different battery technologies, in order to perform their activities, they use the same infrastructure and they establish common relationships among actors involved in the supply chain. Therefore, the existence of criticalities related to the technological aspects does not concern collectors. Indeed, their role is to ensure that spent batteries will not disperse into the environment in order to prevent environmental pollution.

Finally, analyzing recyclers there is a difference in terms of *Infrastructure* (F5) mainly because the LIB system is characterized by a lack of recycling infrastructures both in terms of capacity and proper technologies able to manage the LIBs. Moreover, LIB recyclers highlight the importance of quality of recovered materials (F8). As mentioned for LAB manufacturers, recyclers of LIB are worried about the possibility to obtain from recycling a low valuable product contaminated by different materials. The reason is mainly economic: with a low quality recycled materials and a consequent low selling price, recyclers are not able to cover the recycling costs faced.

The only factor considered important by all the actors is *Legislation* (F3). Indeed, all actors unanimously agree on defining regulations as a fundamental driver which allowed to create the system presents nowadays.
Finally, the other factors are considered in the same way by both the actors of the two systems. In particular, both LAB and LIB manufacturers consider important the *Organizational Set Up* factor (F4) since they are obliged to fulfill the obligation to take

back their spent products according to the EPR principle. Instead, LIB and LAB recyclers attribute more importance to *Technological Aspects* (F1), *Volume* (F2) and *Financial Aspects* (F7) since their final aim is the profit maximization.

Table 17: Comparative analysis between the evidence of factors affecting the CLSC for the two systems according to the different supply chain positions.

SC positions / Factors	M-LAB**	M-LIB	C-LAB	C-LIB	R-LAB	R-LIB
F1*	x	xx			xx	xx
F2					xx	xx
F3	xx	xx	x	x	x	x
F4	xx	xx	x	x		
F5			x	x		x
F6		x	x	x	x	x
F7	x				xx	xx
F8		x			x	xx

*F1-F8: are the factors described in Chapter 2 (Section 2.6)

** M-LAB/M-LIB: LAB/LIB manufacturers; C-LAB/C-LIB: LAB/LIB collectors; R-LAB/R-LIB: LAB/LIB recyclers.

Focusing on Table 18, instead, there is the definition of enablers and bottleneck conditions for both the systems (LAB and LIB) classified according to the different factors.

The result is that for *Technological Aspects* (F1), *Volume* (F2), *Financial Aspects* (F7) and *Quality* (F8) there is a quite opposite situation. In fact, if these factors are seen mainly as enablers from LAB actors, for LIB actors there are see mainly as bottlenecks. Instead, *Legislation* (F3), *Organizational Set Up* (F4), *Infrastructure* (F5) and *Companies Interactions (*F6) are characterized by similar considerations for both the systems.

The main difference between the two systems is that the LAB is seen as a source of value by the actors involved in the CLSC of such product. In fact, the LAB, with its simple and standard configuration (F1), with the availability of a standard technology able to recycle lead-acid batteries in an easily way (F1) and with the presence of remarkable flow of EOL products in the market (F2), is able to guarantee a source of revenues (F7) for the players involved in this particular system. The LIB, instead, is considered a source of costs characterized by different issues. In fact, all the enablers conditions described for the LAB, in the case of LIB are bottlenecks. Indeed, so far in the market there are different varieties of LIB technology (F1) which feed different recycling technologies (F1). Not only the technological considerations are problematic; the volume (F2) is a critical factor for the implementation of a CLSC for LIBs. The small volume of EOL LIBs is not able to allow LIB actors to gain money. Moreover, the high volatility of the lithium market price is a further factor of uncertainty of the system.
Finally, also F8 is fundamental for the determination of the CLSC. In fact, the high purity of recycled lead and its lower price compared to the virgin one push battery manufacturers to buy secondary lead. Instead, so far recovered especially for lithium and manganese (albeit in very small quantity) are not seen valuable recycled materials due to the contamination of other materials.

The other factors, instead, are quite similar. In both the systems, there are players that are obliged to fulfill the requirements of take-back EOL batteries (EPR, F4) according to the set of regulations (Battery Directive and further integrations) defined at the European and at the National levels (F3). Moreover, the different actors involved in the two systems use the same infrastructure (F5) for what concern the collection activities. However, this has a double valence: a positive one, if we consider that using the same infrastructure, actors involved in the system can perform collection activities efficiently and a negative one, if we consider that the sharing of infrastructure can create problems of mixing batteries flow and thus creating problems at the recycling plant stage.
Finally, the actors in both systems agree on seeing the relevance of F6. In fact, the possibility to define relationships among the different players of the SC allows to establish collaborative environments and to favors the exchange of technical knowledge and information.

Table 18: Enablers and Bottlenecks conditions for each factor and for each battery system.

<table>
<tr><th>Factors</th><th>Enablers & Bottlenecks Conditions</th><th>LAB</th><th>LIB</th></tr>
<tr><td rowspan="2">F1
Technological Aspects</td><td>ENABLERS</td><td>• Standard and simple battery design (M);
• High lead concentration (65%) (M);
• Standard recycling technology (R).</td><td></td></tr>
<tr><td>BOTTLENECKS</td><td>• Recycling technologies: high energy consumption and environmental pollution (R).</td><td>• Complex product design (M);
• High variety of materials, compounds and chemicals in the battery (M);
• Different technologies among manufacturers (M);
• No product standardization (R);
• No standard recycling technology (R)
• High level of pollutions (R).</td></tr>
<tr><td rowspan="2">F2
Volume</td><td>ENABLERS</td><td>• Technology maturity (M);
• Low market price of batteries (M);
• Lead recycled materials is preferred than virgin lead (M);
• Well-structured collection system and presence of take-back regulations (C);
• Presence of take-back regulations (R);
• High valuable recovered materials (R).</td><td>• Future remarkable EOL LIB volumes are expected (C, R).</td></tr>
<tr><td>BOTTLENECKS</td><td>• Extension of product life cycle (M, C);
• Uncertainty based on the collection system and illegal flows of EOL batteries (C);
• Uncertainty about product returns (time and volume) (R).</td><td>• Secondary use of LIB (M);
• Price of virgin lithium cheaper than the price of the recycled one (M, R);
• Uncertainty about EOL LIBs (quantity, time) (C);
• Secondary use of LIB (C, M);
• Illegal flows (C);</td></tr>
<tr><td rowspan="2">F3
Legislation</td><td>ENABLERS</td><td>• Battery Directive (M);
• Take-Back legislations (C, R);
• Fulfillment of recycling rates (R)</td><td>• Battery Directive (M);
• Take-back legislations (C,R).</td></tr>
<tr><td>BOTTLENECKS</td><td></td><td>• Lack of precise regulations for managing LIBs (C);
• Lack of precise regulations for recovering materials from LIBs (R);
• Fear about future restrictive regulations (in terms of new investments) (R).</td></tr>
</table>

Factors	Enablers & Bottlenecks Conditions	LAB	LIB
F4 **Organizational Set Up**	ENABLERS	• EPR (M, C, R); • Different types of collection networks (M, C).	• EPR (M, C, R);
	BOTTLENECKS		• Wrong way to define the fee (EPR) (M, R).
F5 **Infrastructure**	ENABLERS	• Collective Infrastructure (sharing) (M, C); • Sharing of infrastructure with other products (C); • Link between manufacturers and recyclers (C); • Well structured recycling infrastructure (R).	• The collection system is well-performing (M).
	BOTTLENECKS	• inclusion of LIBs in the input stream of secondary lead smelters (C, R); • leakage of collected items for illegal recycling (C).	• Sharing of the infrastructure with other battery technologies (M, R); • A recycling infrastructure is missing (C).
F6 **Companies Interactions**	ENABLERS	• Sharing of information between SC actors (M, C, R); • Transparency and coordination to prevent potential accidents (R); • Competition with mining companies (R).	• collaboration and information sharing with other actors involved in the SC (M, C, R); • Competition with mining companies (R).
	BOTTLENECKS	• Sharing could generate problems between LAB and LIB (C, R).	• Sharing could generate problems between LAB and LIB (C, R).
F7 **Financial Aspects**	ENABLERS	• Cheaper price of recycled lead compared to the price of virgin lead (M, C, R); • Demand for recycled lead (M, C, R); • Gain from each battery (R).	
	BOTTLENECKS	• lead price volatility (M, C, R).	• Price of virgin lithium cheaper than the recycled one (M, R); • Volatility of material prices (R); • Expensive recycling technologies (R); • Manufacturers are using cheaper material for the production of new batteries (R).
F8 **Quality**	ENABLERS	• High purity of recovered lead (M, R);	
	BOTTLENECKS		• High standard of material purity are required (M); • Recycled materials contamination (R).

Lastly, based on the analysis of evidence of each factor overtime (Section 4.2.3 for LABs and Section 5.2.3 LIBs), Legislation (F3), Organizational Set Up (F4), Infrastructure (F5) follow the same course of actions.

For what concern the *Technological Aspects* (F1) the lead-acid battery does not present relevant modifications. LAB manufacturers were focused on the optimization of battery performances and LAB recyclers introduced small changes in the recycling process in order to reach higher level of operational efficiency in order to reduce both energy consumption and environmental pollution. Instead, since the LIB is a recent technology, so far, LIB manufacturers have not implemented relevant changes in the battery design and LIB recyclers are still working in the definition of a recycling technology able to recover all the materials embedded in the lithium-ions battery.

The factor related to Companies Interactions (F6) presents important implications especially in the LIB system, in which in these years collaboration among LIB manufacturers, collectors and recyclers is seen as a possibility to jointly identify solutions to solve the problems linked with the technological issues and the quality (F8) of recycled materials.

Finally, Volume (F2) and Financial Aspects (F7) are affected by contingent factors. The former is affected by the increasing selling of petrol and electric vehicles into the market and the latter is characterized by high volatility of prices (in particular for lead, lithium, cobalt and nickel).

In conclusion, the bottlenecks that come out by the performing of such comparative analysis are very important because they serve as indications for actions needed to develop the CLSC for LIBs. Moreover, important insights are suggested by the enablers of LABs which provide important evidence of conditions that support the development of a CLSC for batteries.

A further discussion is provided in the next Chapter, where a framework for closing the loop of LIBs is provided.

Chapter 7
Framework for CLSC for LIB development

Based on the comparative analysis performed in Chapter 6, which are the lessons learned that the LIB system could implement in order to define a successful CLSC for the EOL automotive LIBs?

First of all, a standardization of the technology is needed, both in terms of product design and recycling technology. The LIB manufacturers have to work in order to define a product characterized by a minimum number of components, standardizing materials and formats and avoiding the utilization of toxic metals such as cadmium, halogens and others. Moreover, instead of welds, manufacturers have to use nuts and bolts in order to ensure the performing of easily separation activities. These modifications will allow to scale back not only the problems associated with the recycling of EOL LIBs but also the problems of recycled materials contamination. In fact, this study provides empirical evidence to what was highlighted by Richa et al. (2014): with less different materials but more in quantity, the problem of secondary material purity will be reduced and recyclers will be more incentivized to recover larger quantity of the same material.

These changes at the battery design allow recyclers to carry out simpler recycling activities. Moreover, in order to exploit the maximum benefits, Li-batteries manufacturers and recyclers have to work together in the definition of a common solution which can bring benefits to both the players (Rahimifard et al., 2009). To do this, the manufacturer's vision need to change. Rather than a burden imposed by legislation, recycling need to be seen as an opportunity for manufacturers to sustainably increase the access to the raw materials needed for their future production (e.g. lithium, cobalt, manganese and others). In fact, the value chain principles of design for recycling and remanufacturing products starts at the design stage. Therefore, the activities of dismantling and components separation must be foreseen at this stage of the product development as mentioned Heelan et al. (2016) in their study.

Therefore, a shift from a material-centric approach to a product centric approach is needed.
The product centric approach is focused on the recovery of all the materials that a product is made. This approach tries to overcome the complexity related to the identification and separation of all the materials from highly mixed products (UNEP, 2013) shifting from a mass recycling to the recovery of all the materials that made a LIB. In fact, recycling activities have become increasingly difficult and much value is lost because of the growing complexity of products and complex interactions within recycling systems. The introduction of this new approach will be a remarkable step towards resource efficiency and efficient recycling system. Moreover, this change of perspective would allow the recycling of lithium.

LABs are composed by few different materials and in large quantity (e.g. 65% of a LAB is lead) and therefore, the recycling activities are very simple and standard. Instead, LIBs are made by a huge variety of materials and they are present in small quantities and with different chemists. These issues push LIB recyclers to extract only some of the materials embedded in the battery based on their value and facility to extract (e.g. copper, cobalt, nickel). Materials like lithium and manganese are lost. Therefore, the focus needs to be shifted to the recycling of entire products at their end of life instead of focusing on the individual materials contained in them.

Possible solutions could be the implementation of separation technology for recovered cells that enables processing different chemistries, the definition of recycling processes for each cell chemistry and the introduction of methods for the separation of cathode materials after initial processing.
A successful solution for closing the loop could come from one of the ongoing works on the search for an alternative recycling technology. In particular, two projects can be reported:

- ✓ In Italy, Cobat and CNR (in particular the ICCOM division, the "*Istituto di Chimica dei Componenti Organometallici*") are jointly working on the definition of a new, reliable and eco-sustainable recycling technology able to recycle all the materials which made a LIB (Cobat, 2017).
- ✓ In Pennsylvania (USA) some researchers discovered the existence in nature of particular types of mushrooms capable of making the LIBs biodegradable. Indeed, researchers discovered that lithium and cobalt can be extracted thanks to the combination of three mushrooms such as the *Aspergillus niger*, the *Penicillium simplicissimum* and the *Penicillium chrysogenum* (University of South Florida, 2017).

Moreover, in order to proper perform a successful CLSC, new regulations are needed. The introduction of the Battery Directive (2006) and the further integrations were fundamental for the establishment of the infrastructure that is in place nowadays but, new efforts from both European and National institutions are needed. This finding confirms indications from Rahman and Subramanian (2012) and Gaines (2014) about the necessity to set new targets for collection and recycling in order to ensure a remarkable flow of EOL batteries to manage. In particular, specific rules are needed for recyclers of LIBs. The current minimum recycling rate for LIBs is 50% and recyclers are able to reach recycling rate of more or less 65%. This means that the current regulations need to be revised and additional targets must be set especially focusing on the materials that must be recovered (for example lithium, no companies extract lithium since it is not convenient). Moreover, new regulations must be designed in order to foster and stimulate recyclers to make investments in new technologies, maybe with the introduction of some incentive mechanisms. In fact, recyclers do not make investments since they are worried about the possibility that restrictive regulations could affect their business activities. Finally, governments have to set clear and severe laws against illegal flows of EOL batteries in order to allow to recycle as many products as possible.

In addition, in order to increase the collection system reliability, the manufacturer according to the design for recyclability can include a label on the battery in order to solve the problem of volume mixing contamination.

Going further in the analysis, Volume (F2) and Financial Aspects (F7) are two important factors that determine the success of the CLSC of EOL LAB. In fact, high volume of end-of-life products allows the recyclers to exploit economies of scale and operational efficiency. However, so far the volume of EOL LIBs was scant since the automotive LIB is come in the market only some years ago. According to its product life cycle (more or less 10 years) only in a few years, in the market there will be enough volume of EOL batteries to treat. Moreover, recyclers must take into consideration that EOL LIBs can be used as stationary energy storage. This means that an additional delay of some years must be considered by recyclers in order to proper dimension the flow of batteries which need to be treated along the years.

Related to the financial aspects, instead, the situation is affected by uncertainty. The uncertainty comes form the market dynamics and in particular from the volatility of materials prices.

In fact, the LAB market is defined a market with value because virgin lead has a stable and high price on the market compared to the recycled lead that is obtain with low costs by recyclers. This allows the profitability of recyclers and the minimization of supply costs for battery manufacturers.

For the LIB system, instead, since there are different materials with high value, recyclers according to the easiness to perform the recycling activities and the gain from their recovery, they make a prioritization of extraction. As in the case of LAB, LIB recyclers want to maximize their profitability. Therefore, some materials, like lithium, are not extracted for the simple reason that the market price of such materials is not big enough to cover the costs faced during the recycling activities. Therefore, lithium recycling is mainly conditioned by the price that this material has in the market. Indeed, if the price increased over the years (above the "break even point", when revenues from recycling are equal to the costs of recycling process), recyclers would also recycle this material.

In conclusion, for closing the loop of LIB there are some actions that people involved in the LIB system can perform in order to boost the success of the closing perspective of this EOL product. However, some factors like volume and material market price depend on contingent factors and therefore, they are affected by uncertainty: EOL LIBs in terms of time and quantity and market price in terms of volatility.

In the table presented in the next page (Table 19) are summarized the proposed actions for the success of CLSC for automotive LIBs.

Table 19: Framework of actions for the development of a successful CLSC for LIBs.

Factors	**LIB Future Actions:**
F1 - Technological Aspects	• Product design standardization: minimum number of components, standardization of materials and formats and avoiding the utilization of toxic metals; • Design for separation/disassembly: utilization of nuts and bolts instead of welds; • Design of recycling: manufacturers have to shift from a material centric approach to a product centric approach. • Introduction of new recycling technologies able to recover all the materials embedded in the LIB (ongoing projects).
F2 - Volume	• It is a matter of time. A collection system is already present. In order to have remarkable flows of EOL LIBs, operators have to wait some years until the products reach their end of life
F3 - Legislation	• New regulations in terms of: o New targets for collection and recycling (minimum recycling rate) o Incentive mechanisms in order to stimulate recyclers to make investments in new technologies o Measures against illegal flows of EOL batteries
F4 - Organizational Set Up	(no operations are defined)
F5 - Infrastructure	• In order to solve the problem of volume mixing contamination, manufacturers can define a label in order to distinguish the LIBs from the other battery technologies
F6 - Companies Interactions	• Batteries manufacturers and recyclers need to collaborate in the definition of product specifications in order to bring benefits to both of them.
F7 - Financial Aspects	• It is mainly a matter of market dynamics. The driver that conditions the material recovery is the market price.
F8 - Quality	• In order to avoid recovered material contamination problems, the battery must be composed by the minimum number of different materials.

Chapter 8
Conclusions

In these years, great interest is given to the growing trend of EVs deployment. This market growth corresponds to a rapid growth in LIBs demand.
The LIB is a battery technology that contains valuable and scarce materials like cobalt, lithium, manganese, nickel and copper. Many concerns are addressed to the management of this product when it reaches the end-of-life both in terms of environmental and supply security issues. However, many materials are still lost during recovery activities (lithium, manganese and others).
In order to prevent unanticipated events a proactive approach is required for the right management of EOL LIBs in the market. Therefore, through the implementation of a CLSC solution focused on recycling, according to the efforts pushed by the European Commission (EC, 2015), the high environmental issues and the energy use of primary production could be reduced, import dependencies could be diminished and economic valued could be created.
Indeed, the final aim is to define a system, where the value of products, materials and resources is maintained in the economy for as long as possible and the minimization of waste generation is guaranteed.

This thesis addresses the problem of performing a successful CLSC for end-of-life automotive LIBs in which the lithium recycling is performed. By the execution of an analysis over two battery systems, the lead-acid batteries systems and the lithium-ions one, I extend the knowledge on the implementation of a CLSC focusing on recycling as a product recovery option. In particular, LAB system serves as a reference point to further develop a roadmap for the LIB system.

LAB is a very good example since it is recycled more than any other consumer product, especially because lead is a toxic material and its disposal is heavily regulated; indeed, in EU more than the 99% of all lead-acid batteries are recycled (EUROBAT, 2015).

In order to understand the actual situation and examine the systems following the key features of the CLSC, I developed a framework of eight factors to conduct my analysis. I collected information through interviews and secondary data and I considered

European and Italian players involved in the most representatives supply chain positions (manufacturers, collectors and recyclers).

The analysis demonstrates that the two systems have both similarities and differences. Indeed, by making a comparative analysis the result is that, so far, the most critical factors for a proper implementation of a CLSC for LIBs are:

- ✓ the technological aspects (both in terms of battery design and recycling technology),
- ✓ the low availability of EOL LIBs managed by collectors and recyclers,
- ✓ the actual regulations that not provide specific requirements for LIB technology,
- ✓ and the volatility of material market prices that creates uncertainty in the market.

Based on the examination of both LAB and LIB system, I suggested a framework of actions needed to enable the CLSC of LIBs with the performing of efficient lithium recycling activities. Based on this framework, below I provide implications for business actors and policy-makers.

For example, recyclers and manufacturers need to collaborate in order to solve the problems related to the technological aspects. The LIB must be composed by lower different materials and it must be designed according to the principles of design for disassembly/recyclability. In order to solve the problem of volume mixing contamination, LIB manufacturers need to define a label which allows to distinguish LIBs from other battery technologies.

Moreover, my findings could be helpful to policy makers in their efforts to improve the recovery of wasted products. In fact, for the proper definition of a successful CLSC for LIBs further regulations must be set. In particular, new regulations are needed in order to set precise responsibilities among players involved in the system, to incentives recyclers to make new investments in more reliable and sustainable recycling technologies and to sanction illegal flows of EOL LIBs.

However, a number of uncertainties still exist. First of all, it is difficult to estimate exactly the trend of EVs growth and the consequent waste flow of LIBs. Moreover, new trajectories of LIBs battery technology and recycling technologies deployment could bear thanks to recent research. Indeed, particular attention is given to the research conducted by Cobat and CNR, which are trying to define a reliable and eco-sustainable technology for the treatment of EOL LIBs.

Finally, this study presents some limitations and it offers several prospects for further research. First of all, the findings obtained are the result of an analysis that engaged with several companies from three SC positions (manufacturers, collectors and recyclers). Further research will benefit from examination of greater number and type of stakeholders. Indeed, given the multiple stakeholders involved in the battery system who either facilitate the development of CLSC activities or create barriers, and the complexity of their operations and decision making processes, there is large space for further research. Moreover, the actors considered are mainly Italian and European. Therefore, a global picture is missing.

Lastly, as the LIB system is still developing, in the next years there might be technological progress both in terms of battery and recycling technology, more restrictive regulations and different market dynamics (EVs sold in the market, lithium market price), etc. Therefore, the proposed framework should be revised accordingly.

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Appendix 1

List of questions for the interviews

Questions	Manufacturers	Collectors	Recyclers
Which is your experience in the company and which are your responsibilities?	x	x	x
Which position does the company have in the supply chain?	x	x	x
Which functions does the company perform in both forward and reverse supply chain?	x	x	x
Does the company use recycled lead/lithium in production of new batteries? Why? When did the start to do that?	x		
Did they perform the reverse activities in an individual or in a collective way? Which are the synergies that is possible to exploit in the collective way? And the criticalities?	x	x	
Did the company perform also the recycling activities? In which way is the company engage in these activities? Which are the drivers that influence this decision?	x		
Which are the economic factors that affect the recycling activities? Are there economic incentives to perform activities related to reverse supply chain?	x	x	x
Is the battery system forced by regulations/governments laws to perform some specific activities? (e.g. recycling of particular parts of the battery, recovery of particular materials…)	x		x
Which kind of recycling technology does it use? Why/Reasons (certain level of performances, quality of the output, technical feasibility)?			x

Is the battery characterized by a standard design or it is considered a complex product?	x		
Is the battery easily recycled? What is the percentage of lead/lithium recycled? Why?			x
Has the company some collaboration with other companies? Yes or no and why? Which are the factors that you have to consider when you undertake this decision?	x	x	x
How the recycled materials are used? In particular, which portion goes back to battery production?	x		x
Is the quality or recycled material sufficient for use in the same applications?			
There were some fundamental events/facts over the years that change the way in which companies deal with batteries (new regulations, new technologies)?	x	x	x
How did lead companies react against the success of the lithium-ion batteries and the advent of EVs?	x	x	x
How the 2006/66/CE directive change the way of working of companies?	x	x	x
How did companies react after the introduction of EPR (Enterprise Produced Responsibility)? There was a radical change of the entire system?	x	x	x
How does the company address the problem of the LME price fluctuation? Are strategic decisions driven by this fluctuation?	x		x